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CARGO THROUGHPUT AND SURVIVABILITY TRADE-OFFS IN FORCE SUSTAINMENT OPERATIONS
by
William J. Sumsion
June 2008
Thesis Advisor: Fotis Papoulias
Second Reader: Joshua Gordis

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Force sustainment requires an optimum supply of resources to maintain and project power in an area. With sustainment reaching ever farther from the origin of supplies, commanders find an increasing exposure of their logistic trains to risk. To mitigate the increased risk from hostile forces, the survivability of supply vehicles must be considered in force sustainment operations to accurately capture a true throughput projection. Development of an optimum throughput plan for littoral sustainment will reduce overall risk to supplies and maximize throughput to the war-fighter. The research conducted focused on maximizing throughput considering the size, quantity, and risk to the cargo vehicles traversing the littoral arena. The major risk component studied is comprised primarily of littoral mines, though this risk is comparable to many other survivability situations. Use of data collected from computer modeling programs are used to compute and maximize throughput.

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CARGO THROUGHPUT AND SURVIVABILITY TRADE-OFFS IN FORCE SUSTAINMENT OPERATIONS

William J. Sumsion
Lieutenant, United States Navy
B.S.M.E.T., Eastern Washington University
M.S., University of Wisconsin

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requirements for the degree of

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June 2008

Author: William J. Sumsion

Approved by: Fotis Papoulias
Thesis Advisor

Joshua Gordis
Second Reader

Anthony Healey
Chairman, Department of Mechanical and Astronautical Engineering

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ABSTRACT

Force sustainment requires an optimum supply of resources to maintain and project power in an area. With sustainment reaching ever farther from the origin of supplies, commanders find an increasing exposure of their logistic trains to risk. To mitigate the increased risk from hostile forces, the survivability of supply vehicles must be considered in force sustainment operations to accurately capture a true throughput projection. Development of an optimum throughput plan for littoral sustainment will reduce overall risk to supplies and maximize throughput to the war-fighter. The research conducted focused on maximizing throughput considering the size, quantity, and risk to the cargo vehicles traversing the littoral arena. The major risk component studied is comprised primarily of littoral mines, though this risk is comparable to many other survivability situations. Use of data collected from computer modeling programs are used to compute and maximize throughput.

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LIST OF ABBREVIATIONS

ASCC – Autonomous Sustainment Cargo Container

CDF – Cumulative Distribution Function

GWOT – Global War on Terrorism

GPS – Global Positioning System

HSV – High Speed Vessel

IED – Improvised Explosive Device

ISO – International Organization for Standardization

LCAC – Landing Craft Air Cushion

LCU – Landing Craft Utility

LF – Loading Fraction

LST – Landing Ship-Tank

LSV – Logistic Support Vessel

RPGs – Rocket Propelled Grenades

SFC – Specific Fuel Consumption

LF – Loading Fraction

UAV – Unmanned Aerial Vehicle

UMPM – Un-countered Minefield Planning Model

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I. INTRODUCTION AND MOTIVATION FOR USING SURVIVABILITY IN A THROUGHPUT ANALYSIS

A. INTRODUCTION TO THROUGHPUT

1. Background of Naval Cargo Supply

Supplying the warfighter with all the resources required to sustain operations is paramount to any deployed military force. Ensuring that the cargo arrives timely and safely is a major part of sustaining a forward presence. More than ninety percent of U.S. war fighters' equipment and supplies travel by sea [8]. Sea-based supply is also one of the primary missions of the littoral force for the future [7]. Utilizing the maximum available technology and tactics to supply the warfighter will require upgrading our naval supply platforms that still use technology and ships primarily from Vietnam [7].

Though newer waterborne logistical delivery platforms are available in the U.S. Navy inventory, such vehicles may not be able to properly supply through the littorals where significantly higher risk to personnel and watercraft are expected. Craft such as the High Speed Vessel (HSV) and Landing Craft Air Cushion (LCAC) represent a significant capital expense and may be too valuable to risk in certain littoral supply scenarios.

Broadening the U.S. Naval inventory of cargo ships to smaller, cheaper, and more numerous ships provides various opportunities to maximize throughput of cargo. Traditionally, the highest throughput is achieved by maximizing the size of the ship since a larger ship provides for the most efficient means of cargo transport through open water. Once risk from mines or other weapons is introduced, it makes sense to have more cargo ships carry the load so not all cargo is lost in the event of a successful attack.

2. Background of Risk Considerations in Cargo Supply

Force sustainment requires an optimum supply of resources to maintain and project power in an area. With sustainment reaching ever farther from the origin of

supplies, commanders find an increasing exposure of their logistic trains to risk from hostile forces. To mitigate the increased risk from hostile forces, the survivability of supply vehicles must be considered in force sustainment operations to accurately capture a true throughput projection.

Many of the casualties and damages sustained in the Iraq war have been from attacks on vulnerable supply lines, and insurgents have recognized this and increased attacks on such supply lines [6]. The increase in risk from these unpredictable and changing threats requires mitigation. Though supply from naval vessels is different from land supply, many similarities exist. Just as in land supply lines, the Navy primarily has unarmored and vulnerable supply vehicles. The Army and Marine Corps have adjusted to the threat through attempting to minimize risk through survivability enhancements to their supply lines [6]. Such an analysis on naval supply lines and ships seems appropriate given the difficulty and cost to upgrade Army assets in the Iraq war.

B. MOTIVATION

1. Motivation for Risk Assessment

The risk to supply lines is perhaps greatest in the littorals where insurgents will have easy access through low-technology weapons. Researching survivability considerations to supply routes that pass through shallow waters will give the largest benefit for the risks to cargo in the global war on terrorism. This analysis will seek to find how best to supply cargo in the littorals. Highest priorities will be given to maximize throughput of cargo yet minimize threat to human life.

2. Role of Autonomous Vehicles in Risk Reduction

The most promising threat reduction to human life comes from autonomous systems. Such systems have been drastically increased in the armed forces through employment of Unmanned Aerial Vehicle systems (UAV). Such systems allow for areal patrol of a hostile area with effectively zero threat to operator life. This concept could be expanded to littoral supply. In this analysis, autonomous supply vehicles will be

considered due to the potential of risk to human life. This architecture is also loosely compared to existing cargo supply platforms in determining which system of ships gives the lowest risk for the highest cargo throughput capability.

3. Motivation and Introduction to Autonomous Vehicles

As previously discussed, autonomous vehicles offer the potential to drastically reduce the risk to human life in hostile environments. An autonomous vehicle requires no local human control. The vehicle can either be controlled remotely or by programming in coordinate geographic markers that the craft will maneuver through. This can be done via GPS or other local mapping coordinates. By removing humans from the local operating area of the vehicle, there are several advantages and disadvantages.

Advantages to an autonomous system include:

1) Reduced weight of personnel and supporting equipment
2) Reduced human exposure to hostile risk
3) Potential for increased payload for the same size chassis
4) Easier command for fleet control

Disadvantages to autonomous system include:

1) Increased navigational and programming equipment weight
2) Increased technological complexity
3) Higher potential for slower reaction time
4) Easier to be overcome by hostile forces
5) Cost

By far, the biggest advantage is reducing human exposure to hostile risk. Endangering military and civilian re-supply personnel could be severely reduced through developing and operating an autonomous cargo delivery system. Though the disadvantages are not able to be ignored, the potential advantage of reducing life to

humans outweighs most of the disadvantages. The issue of cost is left for further research. Autonomously moving a standardized cargo container, such as the International Organization for Standardization (ISO) cargo container would well suit this risk reduction model since some work has already been done with this standard sized shape, and many of the disadvantages have been addressed to some level with this size as well.

a. Demonstration of Delivery Using a Generic Idealized Box Vessel for Supply in the Littorals

Large cargo ships are many times unable or unwilling to approach littoral costal areas due to several reasons. Such reasons include that they draft too much, they do not want to be within firing range of costal batteries, or minefields prevent them from closer approach. Instead of risking the large ship in this environment, the ship can deploy one or several generic boxed supply vessels. The large ship can either remotely control the vehicle or program in GPS coordinates for the small vessels to navigate. Below is a demonstration of how the vessel might deploy from larger ships into a littoral supply route to shore.

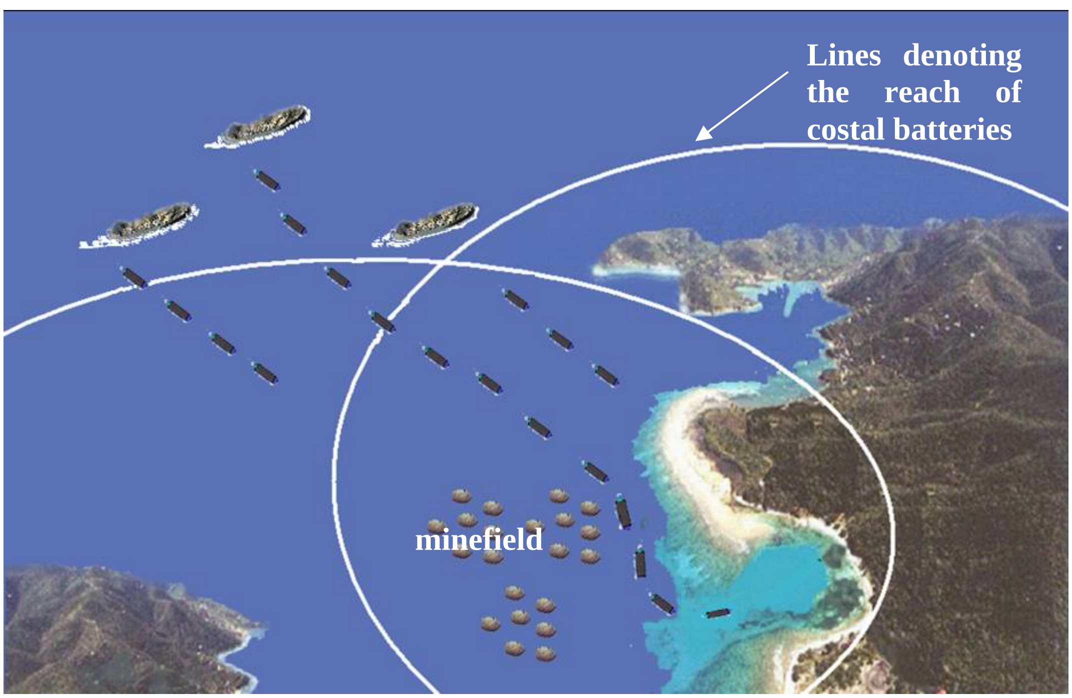

Figure 1. Demonstration of deploying small vessels from larger host ships (from [4])

It is important to note that the vessel can encounter several threats while navigating to the shoreline. These threats are independent of delivery mode, so the vessel allows for delivery without local risk to human life.

b. Dimensions and Sizing Considerations for an Idealized Box Vessel

Sizing an idealized box vessel can be done by using a base size of some rectangular prism or cuboid. Since a great deal of work has already been done with an International Standards Organization (ISO) container, the base sizing of the vessel will be based on these dimensions. These values were rounded from the values published by Tepping [4].

Length (ft)	20
Beam (ft)	8
Height (ft)	8
Displacement (lbs)	52895
LF of 80% displacement (lbs)	42316
Nominal draft at LF of 80% (ft)	4.158

Table 1. Base sizing of a cuboid-shaped vessel (from [4])

Note that the loading fraction (LF) refers to the fraction of how full the vessel is. A loading fraction of 80% means it is full to 80% of the maximum allowed displacement weight. The values of the table above were used as a base model for sizing an ideal vessel. A length factor (l) of one represents the size displayed above in the table. A length factor of two would represent a craft that has twice the dimensions of the above table, and so on. Though they have the same two letters for the first words describing them, it is important to keep the loading fraction (LF) and length factor (l) as two completely separate values. Optimum sizing of a cuboid-vessel is done by varying several parameters and observing optimum points for specific operating areas. This analysis was done and is displayed in part III.

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II. SURVIVABILITY CONSIDERATIONS

A. SURVIVABILITY IN A MINEFIELD

1. Introduction to Sea Mine Operation

Sea mines have been used in every major U.S. war since the American Revolution [5]. Sea mines are both relevant threat to cargo shipping and easier to model than other threat risks. Modeling other risk sources requires many more variables since it requires more correlation with direct human activity. Mines are able to simply ‘sit and wait,’ thus allowing for easier mathematical and statistical representation [5].

Though the survivability of a minefield is what is modeled and discussed, the risk portion of the discussion could be advanced to nearly any hostile risk. RPGs, as an example, are a risk to any shipping vessel due to their relatively slow speed and large size. Though the models presented are for sea mines, it is reasonable to conclude that even RPGs in terms of loss can be modeled as mines. Given certain parameters for loss rates and weapon density, this model may possibly be expanded to give a reasonable risk assessment for such a scenario.

2. Sea Mine Modeling

Sea mine modeling is a practice done by many in the U.S. Navy. Mine warfare models have been conjured from simple to extremely complex. The mine warfare model used for this analysis utilizes the Un-countered Minefield Planning Model (UMPM) as described by Washburn [1], [2]. This model gives sufficient complexity to model mines to give a sufficient approximation to mine threats of all types.

The most basic model of a sea mine is a contact mine. If a ship encounters such a mine, the mine explodes and the ship will be damaged. The certainty of damage stems from the mine touching the ship when it explodes. Mines quickly evolved to allow a higher probability of hitting a ship by finding methods to explode without direct contact

with the mine. Mines are currently designed to explode when sensors detect that they are within the expected damage radius (distance where the ship will be damaged).

Since mines now employ sensors and other devices to trigger detonation instead of direct contact, a contact mine does not realistically reflect mines in the current inventory of most countries. Most mines currently employ both sensors and counting programs to ensure a higher chance of damaging a ship when exploding [3]. Using a simple square wave to simulate mine actuation (as shown in *a(x)* below) is not realistic with any modern mine commonly used. Using a method that is more sophisticated that allows for distance in navigational error (as shown in *A(x)* below) is required when modeling modern mines and is represented below in Figure 2.

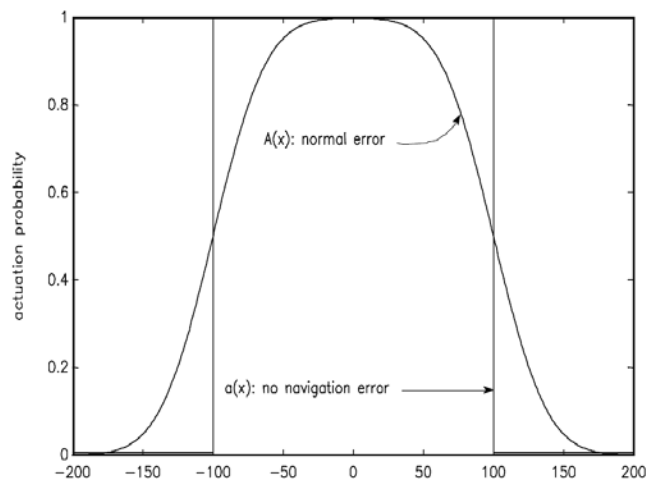

Figure 2. Actuation probabilities *A(x)* & *a(x)* vs. distance *(x)* (from [2])

This curve can be mathematically expressed as:

$$A(x) = E(a(x - U)) \tag{1.1}$$

The letter U is a random variable representing navigational errors and E is the expected value operator. The variable x is thus given as the distance from the track the ship is programmed to follow versus the mine [2]. As Washburn states, due to navigational errors, it is possible for a ship to get lucky and not actuate a mine. For example, at $A(x) = A(100)$ in the diagram above if the navigational error pulled the ship

farther away from the mine, then even though the planned track would explode the mine, there is a probability of only 50% of actuating the mine once navigational error is considered. This reduction in probability is not free, though. Conversely, it is also possible to be unlucky and actuate a mine at *A(150)* due to navigational errors bringing the ship closer to the mine. The curve *A(x)* corresponds to normal navigation errors with mean of zero and a standard deviation of fifty [2]. This is why *A(x)* has rounded corners and *a(x)* does not.

Now that mathematically actuating a mine has been modeled, coordinating the mine actuation to ship damage is done. The variable *d(x)* is introduced as the probability that a detonating mine will damage a ship at a distance *x*. From *d(x)*, the probability that a ship following a determined path through a minefield (*D(x)*) at centerline can be determined by the equation given by Washburn [2]:

$$D(x) = E[a(x-U) * d(x-U)] \tag{1.2}$$

Since the ships will likely travel in groups along the same programmed GPS track, modeling several transitors to the identical path is assumed. A group of *n* ships leads to the equation given by Washburn where $R_n(x)$ is the probability that one out of the *n* number of ships actuates a mine [2]:

$$R_n(x) = D(x)[1-(1-A(x))^n] / A(x) \tag{1.3}$$

$$R_n^* = \frac{1}{b}\int_{\frac{-b}{2}}^{\frac{b}{2}} R_n(x)\cdot dx \tag{1.4}$$

$$x(m+1,k) = R_{k+1}^* x(m,k+1) + (1-R_k^*)x(m,k);\ 0\leq k\leq n \tag{1.5}$$

b = minefield width

It is important to note that this minefield model requires that all ships are assumed to transit the identical intended path. This gives following ships a higher chance of making it through since the previous ship will either prove a path or act as a minesweeper of a mine in the path.

a. Sea Mine Model Example with Graphs

These equations give the foundation for minefield risk modeling. An example output from these equations modeled using Matlab will be shown in detail. To start, several assumptions need to be made about the size of minefield and damage radius of the mine. For this demonstration, the following numerical values were used:

Number of ships (n) = 25

Damage radius (d) = 50

Minefield width (w) = 5000

Number of mines (m) = 250

Maximum Actuation Probability $A(x)_{\max} = ½$

Perhaps the most confusing portion of the minefield modeling inputs comes from the maximum actuation probability input. While discussion has already been given for why this curve is rounded at the edges and not boxed, the curve also may or may not have its maximum value at one. In the explanation of the mathematical model, $A(x)$ was shown as having a maximum value at one in Figure 2. In this problem, $A(x)$ may have a maximum at several values. Commonly $A(x)$ is set to 1/2 or 1/3 in order to model more complex mine systems. This issue has come about due to the increased complexity of naval mines.

Mines have drastically increased their complexity and one such increase in complexity is from counting mechanisms. $A(x)$ can have maximum values at fractions less than one since there may be a counter on a computer chip or other device within the mine to actuate after the first trigger. Despite having a ship that triggers the mine, the mine is programmed to wait for a predetermined number of triggers until exploding. This feature was added to more sophisticated mines in order to attack higher value targets, noting that high value targets are not usually the first through an area [5]. Also, using a value for $A(x)_{\max}$ less than one favors systems with larger ships since it effectively reduces risk for systems with fewer ships. In the graph below, $A(x)$ is shown for the example problem titled Figure 3.

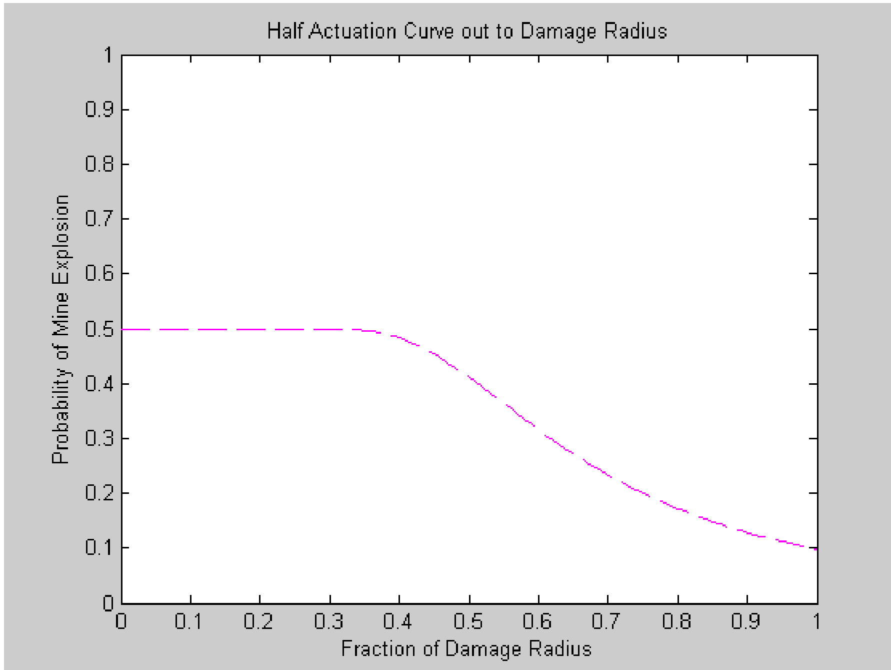

Figure 3. Half-actuation curve out to damage radius for the demonstration problem

The shape of the half-actuation curve can be changed to the specifications desired for each mine type. The demonstration problem used no specific mine as a threat, so a general setting of 1/2 was used for the actuation probability maximum.

The 'threat profile' will give the probability that the n^{th} transitor will hit a mine. That is to say, the first number on the left of the curve will be the probability that the first transitor (ship) will actuate and be damaged by a mine. The second number will be the probability that the second transitor actuates a mine and is damaged and so forth. The output from the initial demonstration values given above are shown graphically below in Figure 4.

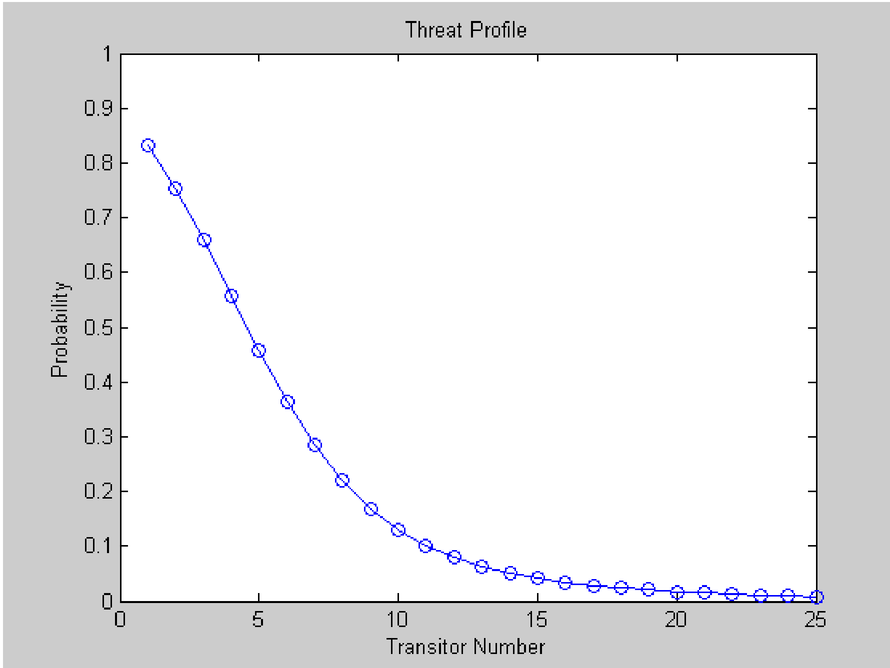

Figure 4. Threat profile for the demonstration problem

The data is also shown below so numerical associations can be demonstrated in Table 2. Notice how the threat to the next following ship is always lower.

Ship Number	Probability of hitting a mine
1	0.8311
2	0.7526
3	0.6594
4	0.5583
5	0.4576
6	0.3648
7	0.2847
8	0.2194
9	0.1683
10	0.1295
11	0.1006
12	0.0791
13	0.0631
14	0.0511
15	0.0418
16	0.0346
17	0.0289
18	0.0244
19	0.0206
20	0.0175
21	0.0150
22	0.0128
23	0.0110
24	0.0095
25	0.0082

Table 2. Threat profile numbers for the demonstration problem

The next curve shown will be the 'casualty distribution.' This shows how many casualties can be expected with their distribution and total probability for each casualty scenario on the y-axis. This is shown below in Figure 5.

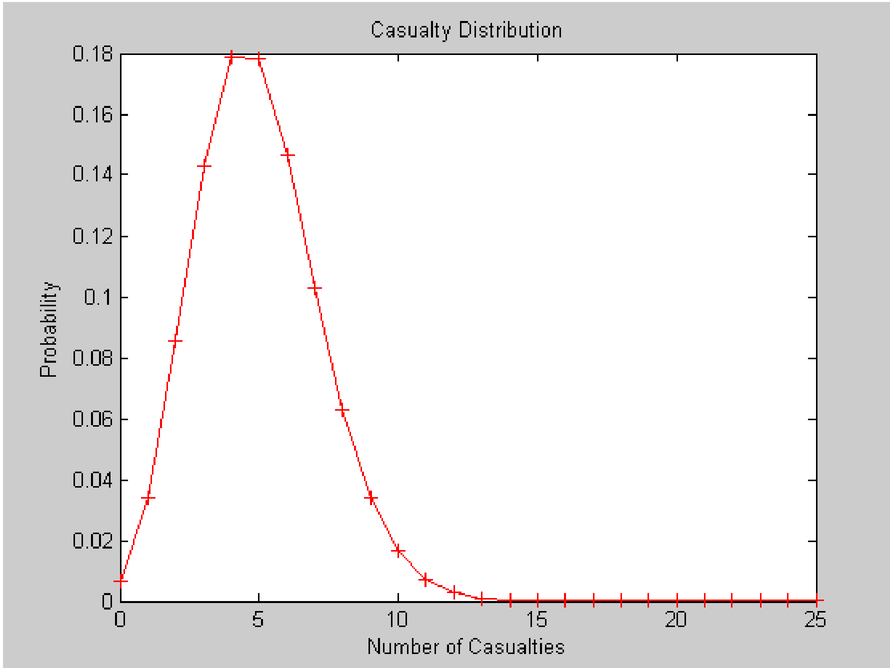

Figure 5. Casualty distribution curve for the demonstration problem

The information displayed in the figure above does not provide much utility in analyzing the minefield risks. It does show which casualty probabilities are highest, and in the example problem the highest probability is for three casualties. This does not give, though, a cumulative number of casualties probability which would be more useful for the throughput analysis, also known as a cumulative distribution function (CDF). To obtain the overall picture for casualty risk, summing the casualty distribution provides more utility. See the results from the example problem below in Figure 6.

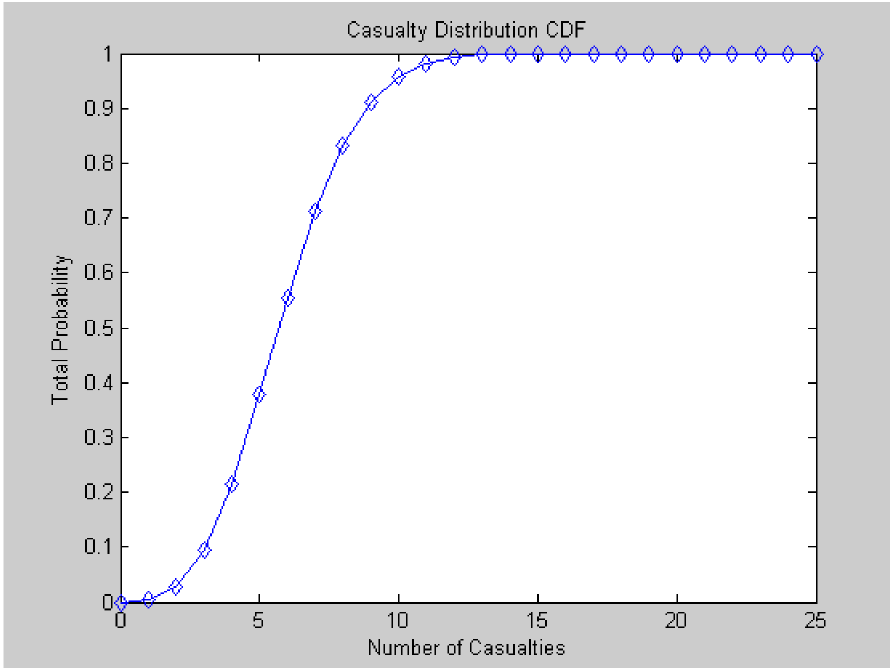

Figure 6. Casualty distribution integration for the demonstration problem

This graph of the casualty distribution gives an output of the threat probability. For example, if a planner wanted to know how many casualties would be expected, then several values could be assessed. The average number of casualties corresponds to the value shown at 0.5 (50%) of "Total Probability" can be found by starting at the x-axis and moving to the right where it intersects with the curve. The intersection shows that on average between 5 and 6 casualties can be expected. This means that half of the time, fewer or equal to 5.5 casualties can be expected. (Note that CDF graphs are typically boxed to show steps in the curve. A curve connecting these points is shown here smoothed.)

This is to say, that the worse luck someone has, the farther to the right they will be on this curve. Someone with extremely poor luck might expect to do worse than 95% of all the runs. In the 95% case, the person could expect about 8 casualties or less with such poor luck. Though the graph never technically reaches 100% unless very few mines are in the water, the curve asymptotically approaches 100%.

b. Sea Mine Model Limitations and Restrictions Using UMPM

Given that the UMPM model is a relatively simple minefield model, there are several limitations to its applicability and usefulness. For this analysis, *d(x)* was assumed to equal one. That is to say, if the mine was triggered at design range, then damage was sustained by the ship and the ship is deemed to have been lost. While such a simplification may be inaccurate, it still provides a reasonable loss scenario without doing shock tests and simulations on the idealized box cargo vessel.

Other restrictions in using the UMPM model do not throw out the use of the model in a survivability simulation. The model is being used to obtain an overall picture of survivability, and specific survival rates for each individual ship are not terribly important. Obtaining an overall view is the real goal with the minefield modeling. Other modeling techniques are able to employ much more sophisticated methods to obtain a higher fidelity picture of the risks to each ship, and also give the operator much more liberty in selecting several of the variables. Such systems are also extremely complicated. For use in this scenario, the limitations of UMPM that include pre-averaging of the actuation curve, inability to change mine types, and non-independent randomness in ship interaction do not significantly degrade the overall risk picture. If more fidelity is needed in risk evaluation with more complicated models, it will be left to future research. The overall goal remains obtaining a reasonable risk picture with a program simple enough to use.

3. Minefield Survivability Considerations and Simplifications

a. Methods of Increasing Survivability

It is important to note that there are several methods to increase overall survivability. Reducing either or both of the vulnerability or susceptibility of the vessel will increase overall survivability. A smaller craft will likely be much less susceptible to attack given its smaller size and, in turn, smaller detection signatures. The fleet of smaller craft in comparing against a fleet of larger craft will also be less vulnerable, since an increase in vessel quantity over other cargo systems is analogous to having several

main engines on a ship. The increase in numbers allows for less vulnerability if hit. An increased number of vessels will decrease overall vulnerability since there are more redundant targets to hit in order for the enemy to enact mission failure.

In the modeling scenario, it is impossible to do a complete survivability assessment since true signatures are not available for the cuboid cargo vessel. Though it will likely have a lower signature, all craft compared are assumed to have an identical signature in actuating the mines in the UMPM model.

b. Complications and Simplifications in Survivability and Mission Failure Arenas

Since the smaller cargo vessels are so numerous, destroying a few will not give mission failure as it would with larger vessels. If a few or even one vessel were destroyed with larger vessels, then all or most of the cargo is lost. With the smaller vessels, only a small portion of the cargo is lost.

There is the complication, though, that smaller ships would likely dedicate their cargo for a specific cargo type. For example, if there are twenty cargo ships carrying supplies to shore for a marine camp, then one ship might be dedicated to carrying fuel, while another might only carry ammo, and so forth. The complication arises if a ship is destroyed that is carrying a specific supply where there is no redundant ship for that same type of supply. In this case, if only one ship was carrying ammo for the marine base and it was destroyed, then mission failure may result from destroying only one ship. For the analysis, it was assumed that the cargo is dispersed evenly amongst all cargo ships, such that if any one was lost it would only impact a fraction of each cargo type.

While this assumption is not likely realistic, it is the only available assumption in using the UMPM model. Various ship types and threat types can be modeled as proved by Monach and Baker, but such a complicated modeling scenario is left for further research if needed in the future [3]. The UMPM model, even with this simplification, gives insight to the proper sizing and risk to transiting ships.

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III. CARGO THROUGHPUT EVALUATION WITH SURVIVABILITY CONSIDERATIONS

A. INTRODUCTION TO A THROUGHPUT ANALYSIS

1. Introduction to Throughput

An analysis of throughput essentially is an evaluation of the amount of cargo that a system can move per unit time. Several factors affect the throughput when considering the size of a craft.

Maximizing speed, cargo, sizing, and fuel consumption are the primary methods of maximizing throughput. There are some tradeoffs, though, when optimizing. Consider, for example, speed. While increasing speed, it takes less time per transit. This increases the amount of cargo that can potentially be taken in a given time period. Increasing speed also will likely use more fuel, so less tonnage will be available for cargo. For the sizing analysis, cargo space is simply defined as the load weight minus the fuel weight. For very fast speeds or very small vessels, fuel will be the only weight carried. In such a case, the throughput will be shown as zero in the analysis.

2. Methodology in the Throughput Analysis

Comparing vessels of various sizes in a throughput analysis was done by starting with a base size as described in section I. B. 2. b. A standard ISO container size was used to allow a single dimension (length) to define all three sides of a cuboid. This sizing was used due to the work already done on the resistance of this size, and the availability of ISO containers worldwide. The size of an ISO container was rounded and defined for the analysis as:

$$\text{Width} = w = 8 \text{ feet} \tag{2.1}$$

$$\text{Length} = \text{L} = 20 \text{ feet} \tag{2.2}$$

$$\text{Draft} = t = [\Delta / w^{*}\text{L}] * (35 / 2240) \tag{2.3}$$

Δ = displacement in tons, 35 = cubic feet per ton, 2240 = pounds per ton

Now all the dimensions of the ship can be defined by a single variable (note that L can be substituted in for w in (2.2), then all can be in terms of L in (2.3)). Once the dimensions are all determined in terms of L, scaling up L will also scale up *w*. Displacement can also be determined with the equation:

$$\Delta = [(\text{Max\_Displacement})*\text{LF})] \tag{2.4}$$

Max_Displacement = 52895 pounds

Additionally, displacement can be scaled by a length factor (*l*), or number of lengths *L*=20 feet, can be defined to scale *l* with displacement (Δ):

$$\Delta = [52895*\text{LF}*(l)^3] / (2240) \tag{2.5}$$

The length factor (*l*) is defined for ease in comparing ships of various sizes that are locked into the geometric shape of an ISO container. This is to say that a ship with a length factor of one will be the size of an ISO container. A ship with a length factor of two will be twice the width, length and draft of a standard ISO container. Using the length factor to demonstrate increasing draft is the main purpose of the defined equations listed above. Now that sizing can be scaled, maintaining a system that is comparable is the next issue.

Finding a method of comparing various sizes and numbers of vessels in throughput requires that there must be some constant across the board. To accomplish this, the total displacement of all vessels in each system needed to be compatible. That is to say, if a ship is four times the displacement of a smaller craft, then the comparison between the two will be four small craft and one large craft. These two different craft will have different efficiencies in moving through the water since larger craft are more efficient. Both systems of delivering cargo will need to carry their own fuel. This is prejudicial against the smaller craft since they need more fuel per ton of cargo carried due to smaller sizes being more inefficient. This means that while displacement is constant for the comparison, the cargo is not constant. Recall that cargo is displacement minus fuel weight. These relationships are shown below as:

$$\text{Payload} = \Delta - \text{fuel} \tag{2.6}$$

$$\text{Constant} = \Delta_{ship} * n = \Delta_{system} \tag{2.7}$$

$$\Delta \;\; \alpha \; (l^3 * n) \tag{2.8}$$

n = number of ships

Obtaining the total resistance to calculate the horsepower required was done by using data provided by using previously calculated values for a boxed shipping vessel done by Yeh [10]. This gave the EHP at a certain speed and size of a craft with a length factor of one. Using this, the EHP calculation was expanded to include variation in displacement and length by using the relationship:

$$\text{EHP} = \text{constant} * (\text{speed})^3 * \Delta_{ship}^{\;(2/3)} \tag{2.9}$$

The constant was calculated in using Yeh's values listed below in Table 3.

length factor (l)	Displacment (tons)	EHP (5 knots)
1.00	23.6	40.8744

Table 3. Values to calculate constant in EHP equation (from [20])

The EHP values from equation 2.9 are then used to calculate the fuel. To do this, a propulsive coefficient of 0.4 was used, and along with the following equations yielded the fuel required:

$$\text{Power} = \text{EHP} / (\text{Propulsive\_Coefficient}) \tag{3.0}$$

$$\text{Fuel} = [\text{SFC} * \text{Power} * (\text{transit time})] / 2240 \tag{3.1}$$

SFC = Specific Fuel Consumption (lb/hr/HP)

Once these equations were programmed in to the software, varying ship size by the length factor yielded the results to demonstrate optimum sizing as is demonstrated subsequently.

a. Ship Sizing and Length Factor Considerations for Meaningful Output

In comparing size and number of the craft, it is important to change only the length factor to calculate the displacement. The results are displayed with the length factor on the x-axis and the throughput on the y-axis. The higher the length factor on the x-axis produces a larger ship. Also, a larger length factor produces fewer ships. In the figure below, it demonstrates how as the displacement per ship goes up, the number of ships go down. The ships are scaled by the length factor (*l*).

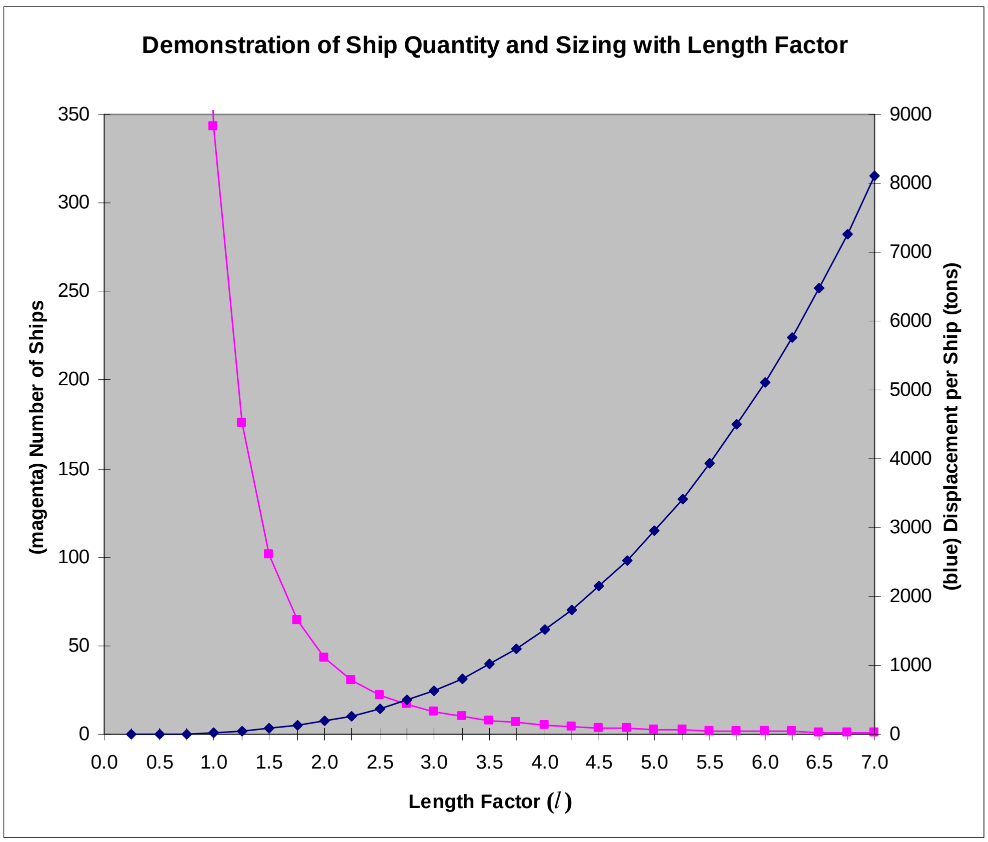

Figure 7. Ship Quantity and Sizing versus Length Factor

The numerical values listed above for displacement are important for some of the calculations later on. For convenience, the values for the displacement are listed below in Table 4.

length factor (*l*)	Displacment (tons)
0.25	0.4
0.50	3.0
0.75	10.0
1.00	23.6
1.25	46.1
1.50	79.8
1.75	126.5
2.00	188.9
2.25	269.0
2.50	369.0
2.75	491.1
3.00	637.6
3.25	810.6
3.50	1012.5
3.75	1245.3
4.00	1511.3
4.25	1812.8
4.50	2151.8
4.75	2530.8
5.00	2951.8
5.25	3417.0
5.50	3928.8
5.75	4489.3
6.00	5100.6
6.25	5765.1
6.50	6485.0
6.75	7262.4
7.00	8099.5

Table 4. Values for length factor and total displacement

The equations and methods listed now give a foundation to initiate a throughput analysis. Comparing various ship sizes with their throughput capacity is subsequently done.

b. Minefield Density and Risk Considerations with the UMPM Model

In incorporating the UMPM model, it was desired to show several risk categories. Clearly some minefields are riskier to traverse than others, so a variety of minefield densities were desired to show the impact on minefield density with the optimum length factor. Several assumptions were made considering the size and type of minefield to introduce risk to the throughput analysis. These assumptions were:

Assumptions for Minefield Geometry and Sizing	
Lethal radius of mines:	54.68 yards (50 meters) [9]
Width of channel:	2025.33 yards (1 nautical mile)
Low density minefield:	10 mines
Intermediate density minefield:	50 mines
High density minefield	250 mines

Table 5. Minefield sizing assumptions

The assumptions were to give a prediction for a generalized geography landscape with various densities. The value for the lethal radius was obtained from Proshkin's discussion on the detection and lethal radius of Russian naval mines [9]. The other values are purely instrumental and have no correlation to an actual minefield. These values were chosen to reflect a wide variety of minefield possibilities. The UMPM model disperses the mines equally in the given space, and the only sizing variable required for a two-dimensional space is the width. The assumption in the UMPM model is that the ship transits directly through the middle for the entire length of the minefield. Since the number of mines given is for the length, it does not matter within the UMPM code if the mine is hit early in transit or late in transit through the field. The only variables of significance to define minefield density are the number of mines and the width of the minefield. Low, intermediate, and high minefield density threat profiles as numerically defined above are graphically shown in Figure 8.

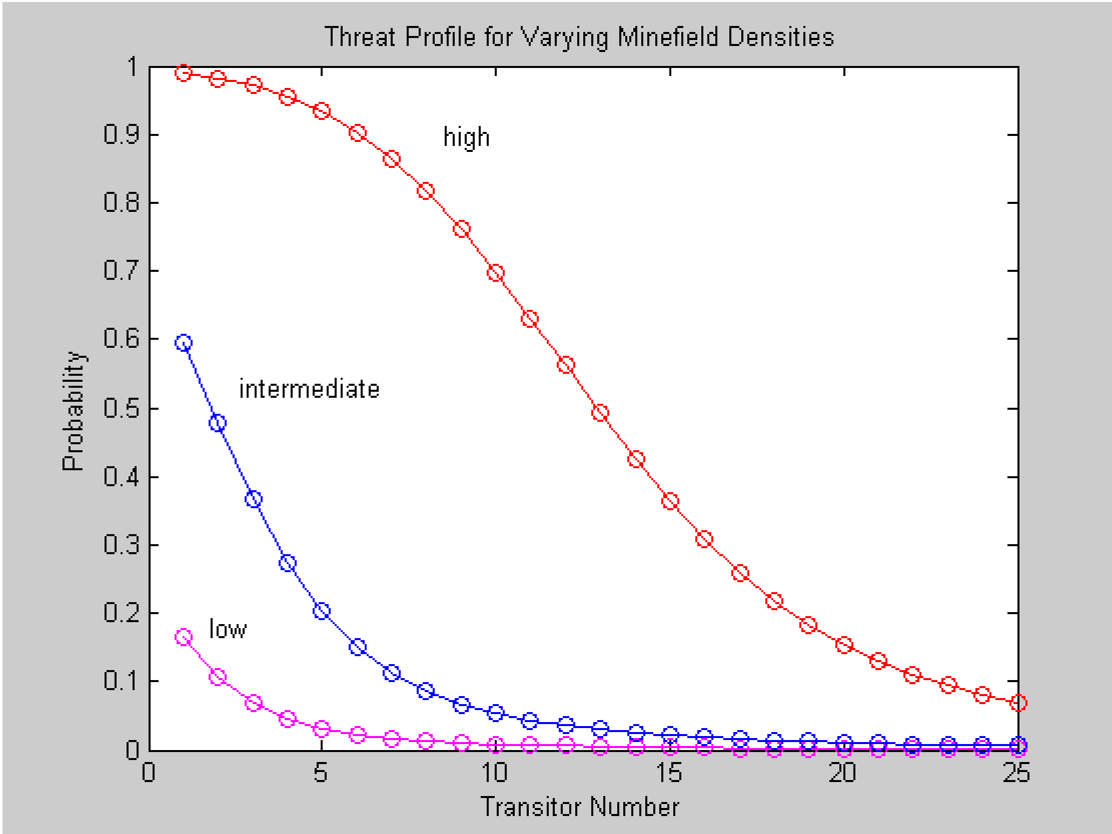

Figure 8. Threat profile for varying minefield densities

Given that the global war on terrorism (GWOT) will likely bring about atypical warfare with non-traditional attacks, it is viewed that a low-density minefield will be a realistic threat to cargo shipping. The ease and low cost of deploying IED-type mines in shallow water remains a real possibility that must be considered. Even areas deemed non-hostile can easily be mined through IEDs by floating them down river or under the cover of night. Intermediate and high density minefields are also a reality, and are included to demonstrate potential throughput without mine abatement. Though this method is unthinkable with manned watercraft, it is a possibility that warrants exploration in a throughput analysis with unmanned craft.

c. Examples of Throughput Curves With and Without Risk

The throughput curve should increase with larger ship sizes, even when holding displacement at a constant. As described before, the total displacement for all

ships of a certain length factor are held constant. Numerical comparisons from calculated values show that it takes 150 ships at a length factor of 1.5 to compare to a single ship of length factor of 7 as shown in the graph in Figure 7. Graphing throughput with the x-axis as the length factor and the y-axis as throughput yields the results in Figure 9.

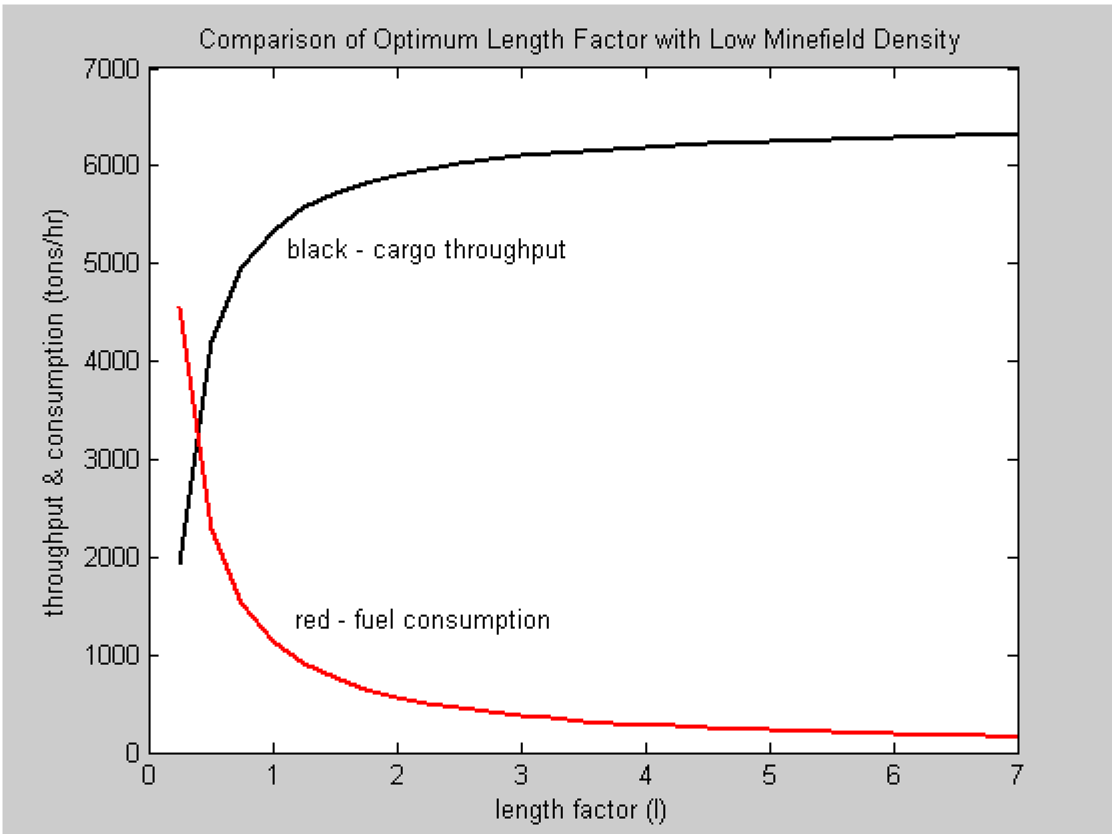

Figure 9. Demonstration of throughput and fuel consumption with length factor

Note how the optimum point for cargo throughput is always increasing. This demonstrates that a higher length factor (l) will be more efficient at moving cargo through water and thus use less fuel. With less fuel on board, more cargo can be loaded and a higher throughput is obtained. In this scenario, few large ships are always the most efficient when compared against many small ships. The small ships simply take far too much fuel to compete with the large ships. The optimum operating point for the above would be a length factor of seven in the above example, but any ship with a larger length factor than seven would win out to what is shown on the graph. The optimum length

factor is therefore infinity. This is collaborated by the shipping industry seeking the engineering and materials strength limits for sizing of their vessels.

Once risk and survivability are considered, however, the curves take a different shape. No longer is it the case where larger ships produce the highest throughput. In the case with survivability and risk, many ships are preferred to few ships. Having a larger number of ships to sink makes the smaller ships more attractive. The goal now is to find the maximum throughput when considering hostile risk. Several curves for throughput are shown while integrating the UMPM model as demonstrated below in Figure 10.

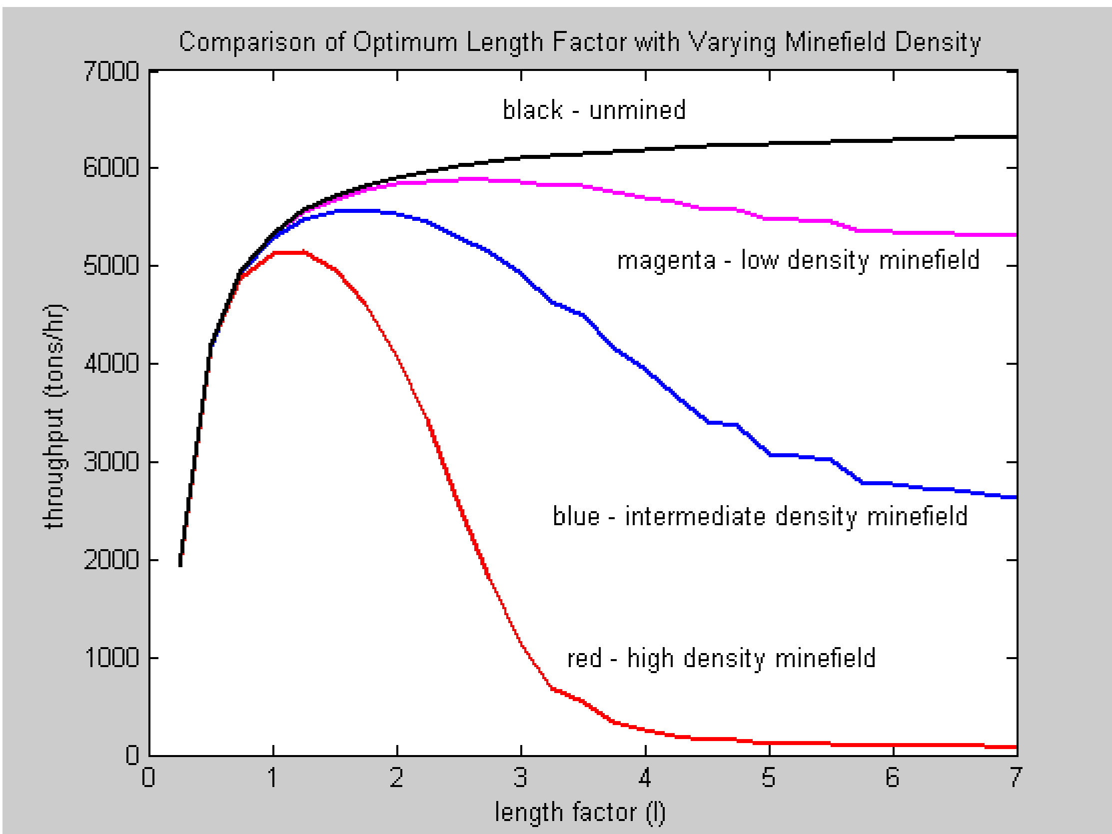

Figure 10. Optimum length factor with varying minefield densities

The results above show that once risk is put into consideration, largest is not always best. The throughput of the smaller ships produced an optimum length factor (peak) roughly between 1 and 3, depending on the density of the minefield. The exact peak values are shown below in Table 6.

Minefield Density		
low	**intermediate**	**high**
2.75	1.75	1.25

Table 6. Numerical values for optimum length factor

More details and results in comparing optimum length factors will be done in the next section. For the example above, the parameters were defined as:

LF = 80%, speed = 30 knots, range = 30 nm, SFC = 0.80 lb/hr/HP

In the comparisons shown later, each of these parameters (LF, speed, range, and SFC) will be varied to show the impact on optimum length factor.

B. RESULTS FROM THE THROUGHPUT ANALYSIS WITH SURVIVABILITY CONSIDERATIONS

1. Results From the Throughput Analysis

The results from the throughput analysis as described previously demonstrated optimum values for ship size and weight.

As previously demonstrated, adding in risk to the throughput analysis yields curves to show the expected throughput. Notice how the magenta, blue, and red curves have a maximum value above in Figure 10.

These maximum values or optimum throughput points represent the best geometry and size of ship for the density of the minefield specified. To further understand the optimum operating values, other parameters were manipulated to see the impact on the optimum length factor. Parameters such as loading factor (LF), range, speed, and SFC were varied. The following figures demonstrate what happens to the optimum operating point as these conditions are changed. It is important to note that the optimum points are rounded to the nearest quarter length factor.

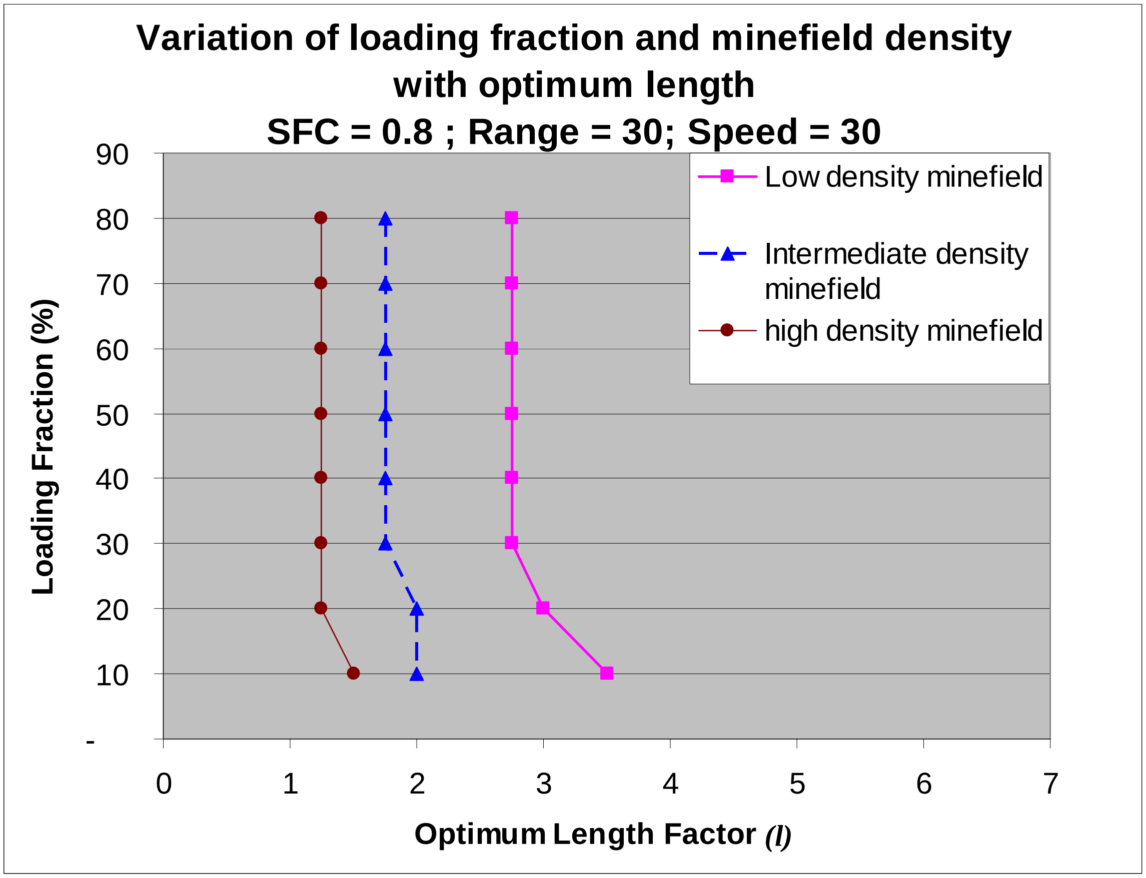

Figure 11. Variation of loading fraction and minefield density with optimum length

The figure above shows that loading fraction has nearly no impact on the optimum length factor until the loading fraction is below thirty percent. The density of the minefield also had a fairly significant impact on the optimum length, as the low density minefield had a length factor 2.4 times larger than that of the high density minefield and 1.7 times larger than the intermediate density minefield. If a ship were to be constructed based purely upon the loading fraction optimum length as shown above, a ship with a length factor of around 1.75 to 2 would best fit what is modeled with the data.

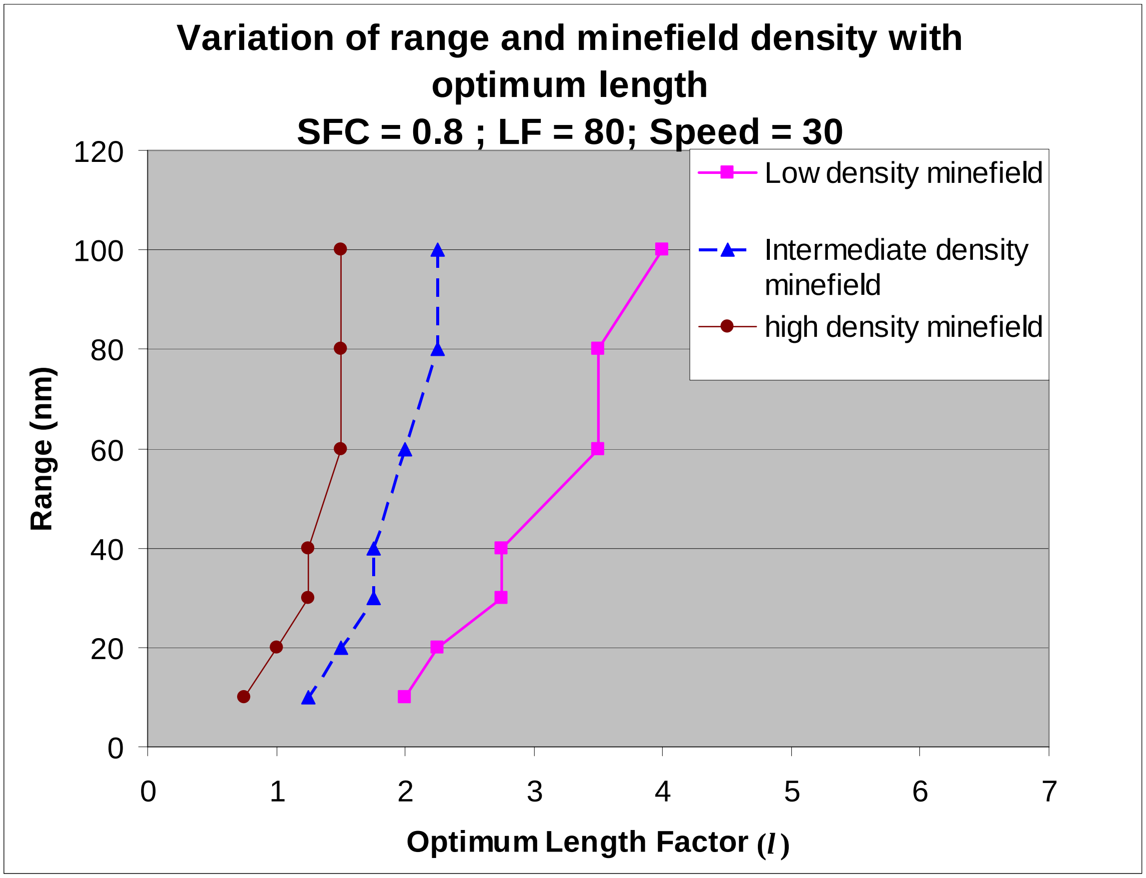

Figure 12. Variation of range and minefield density with optimum length factor

Range has a much more drastic impact than did loading fraction. As range increases, so did the optimum length factor. This is due to the increase in fuel with range. As fuel increases, available payload decreases. This pushes the curves to the right as shown in the figure above. It appears that a reasonable length factor based purely on range should be somewhere around 1.5 to 2 to obtain the optimum operating points across all minefield densities.

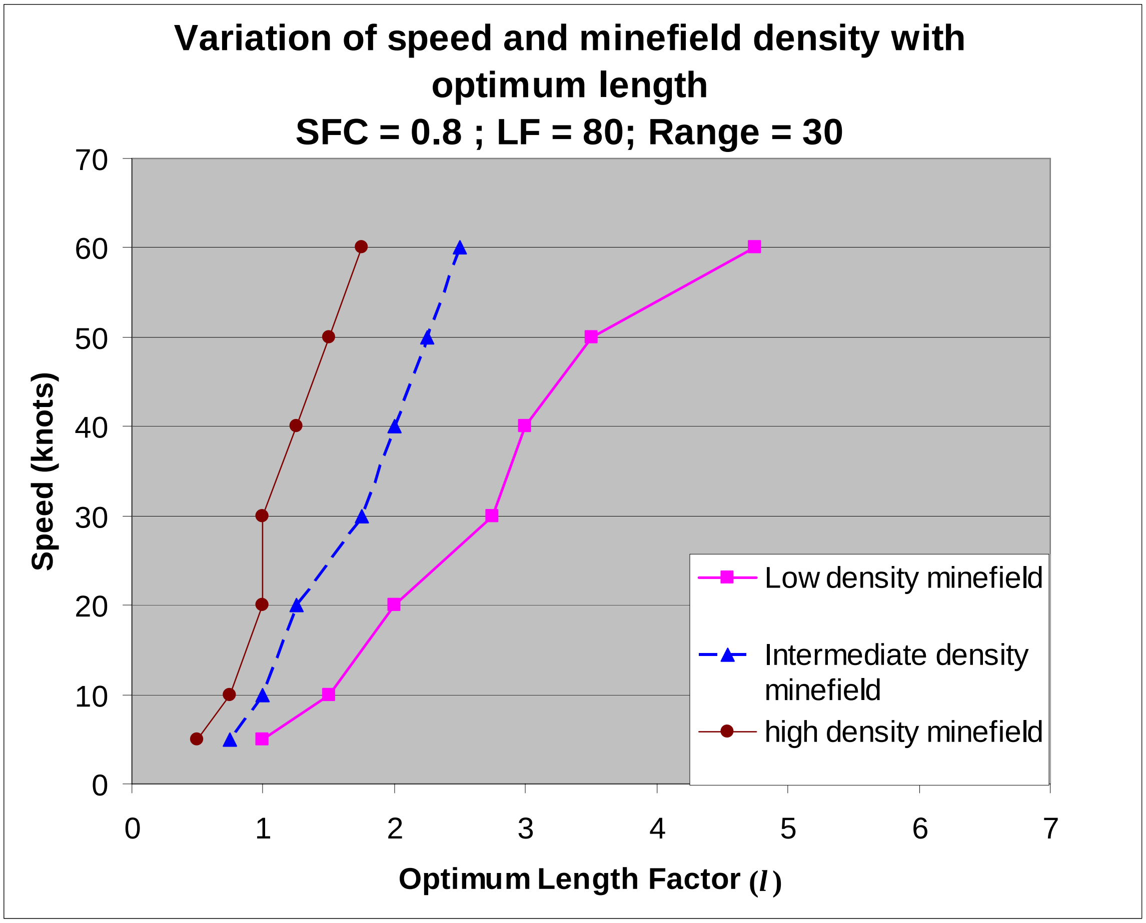

Figure 13. Variation of speed and minefield density with optimum length

Speed has a similar impact on length factor as range. A higher speed requires much more fuel. Speeds in excess of 20 knots drastically increase the length factor since the additional fuel load to maintain such speeds is high. This is even more difficult for the smaller vessels since a larger fraction of the remaining displacement must be dedicated to fuel. This pushes the optimum length factor higher with additional fuel loading. The optimum values vary most drastically with speed, and giving a single value for the wide variation in optimum points with speed alone is not possible. This issue is further discussed in the conclusion.

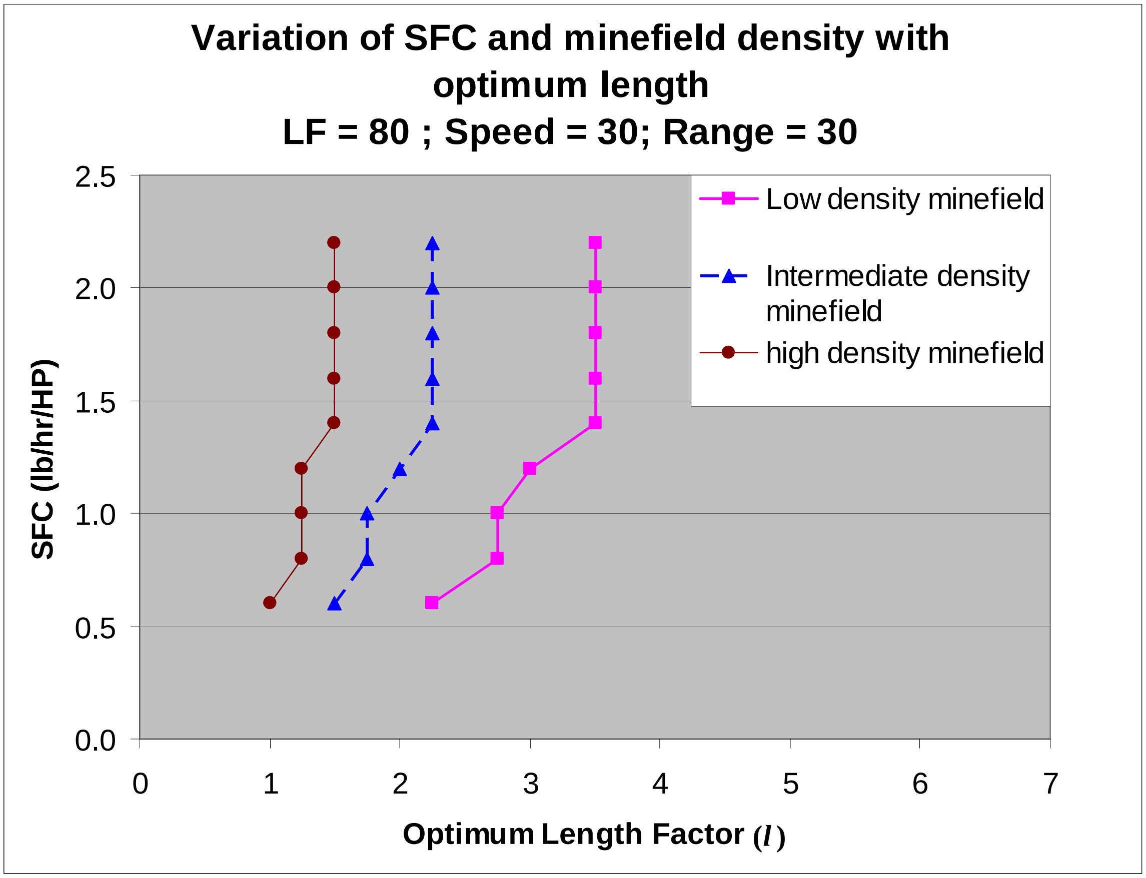

Figure 14. Variation of SFC and minefield density with optimum length factor

As with range and speed, increasing the SFC increases the optimum length factor. As before, the increase in fuel loading also decreases the available payload for cargo. Also note that the increase is not as large for SFC as it is for speed or range. This is since SFC scales nearly linear while speed and range do not. In considering SFC only, selecting a length factor around two appears to best suit all categories of risk and SFC in the range of data obtained.

2. Random Variations with Poor Luck Scenarios

Though the results above give an appropriate view of the *average* expected throughput, it is important to note that the output for a single run could be drastically different when factoring in poor luck. That is to say, bad luck will make the results on a single run look much worse than what is shown above. The analysis strictly reports on

the average of several runs. Such an analysis is good given that no single cargo throughput event requires a specific amount. In such a case where the planner wants to ensure the results are *likely* and not an *average*, it would be more appropriate to run the scenarios with the program set to when the computed risk is 10% or greater, the program will count the run as killed. This type of simulation will be called the "poor luck" simulation.

The values for setting up the poor luck curves are listed below in Table 7.

LF (%)	Speed (knots)	range (nm)	SFC (lb/hr/hp)
80	30	30	0.80

Table 7. Values used to set up poor luck curves

The impacts to the curves are shown below once poor luck is programmed into the throughput program in Figure 15.

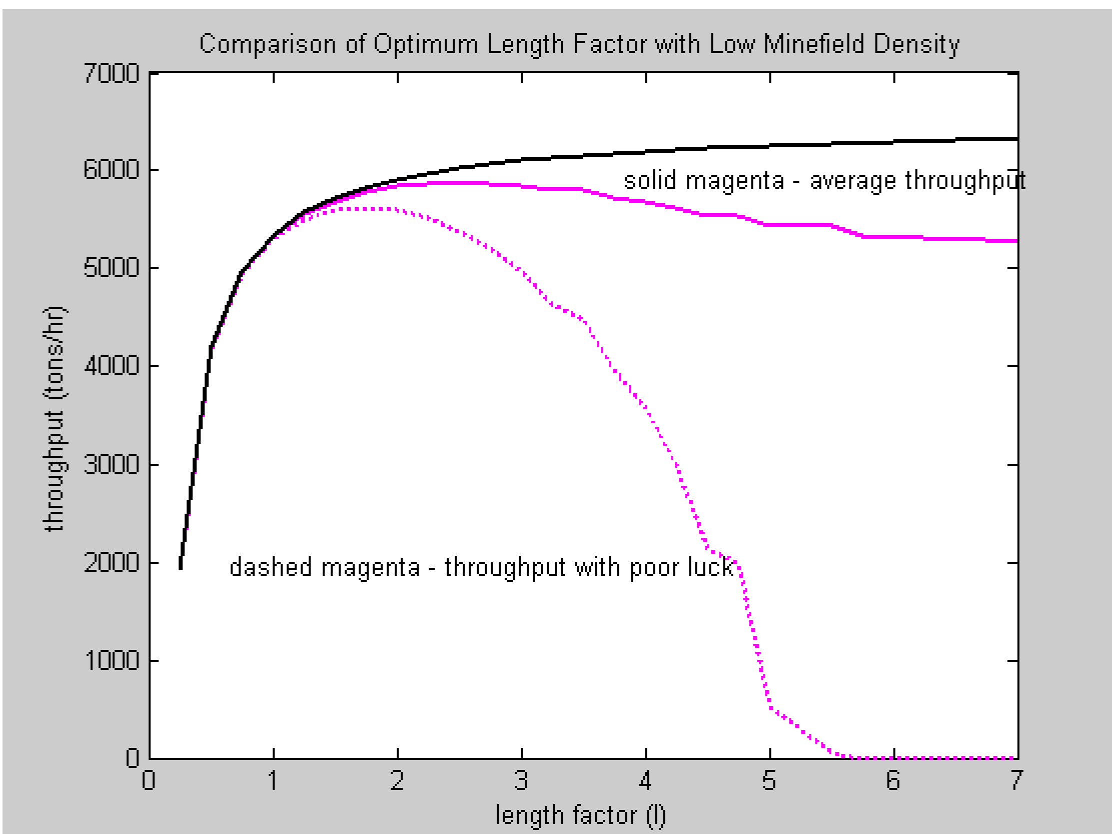

Figure 15. Throughput of low minefield density with poor luck

The other two minefield densities are also shown in the next two figures. Note how the throughput drops to zero for higher length factors. This is due to the first ships having a fairly high risk, and these ships are assumed to have been hit with mines with poor luck factored in. While this remains true for lower length factors, there are several more ships that have the possibility of transiting. Eventually enough ships make it through to still obtain a relatively high throughput.

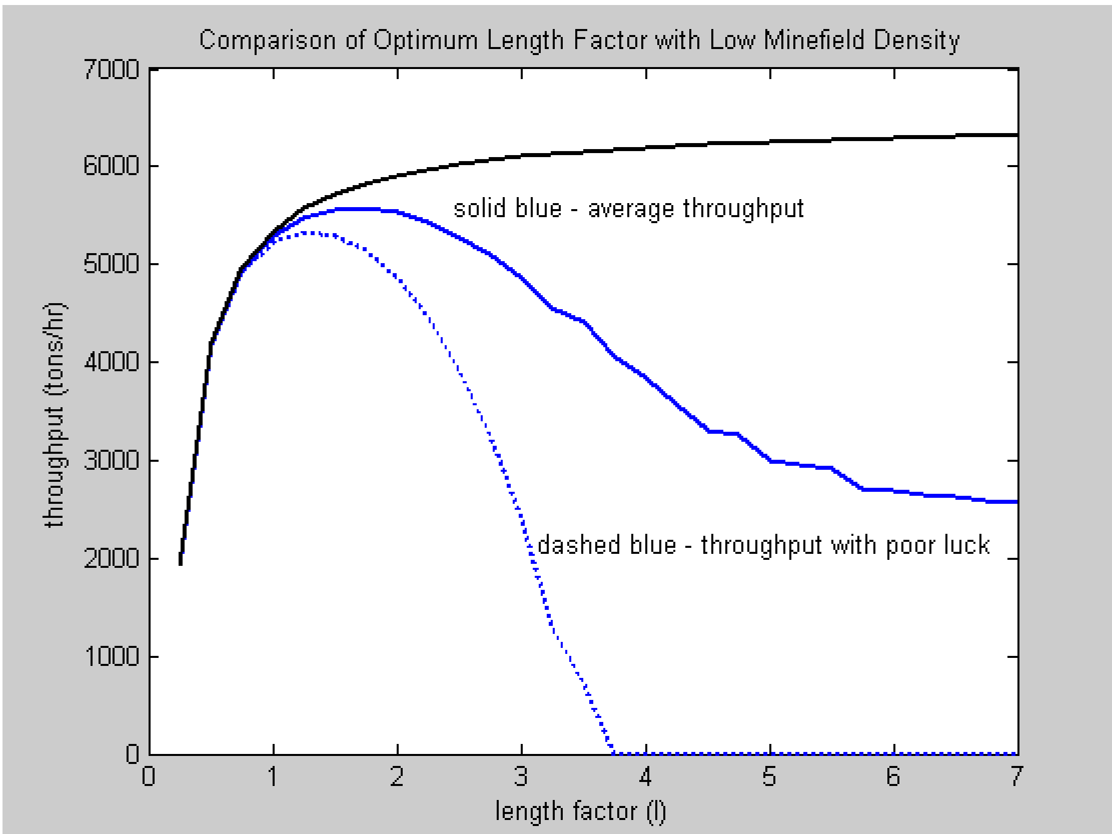

Figure 16. Throughput of intermediate density minefield with poor luck

The intermediate density minefield had a less drastic change than the high density minefield. The results, though, still show that the higher length factors are unfavorable when considering poor luck.

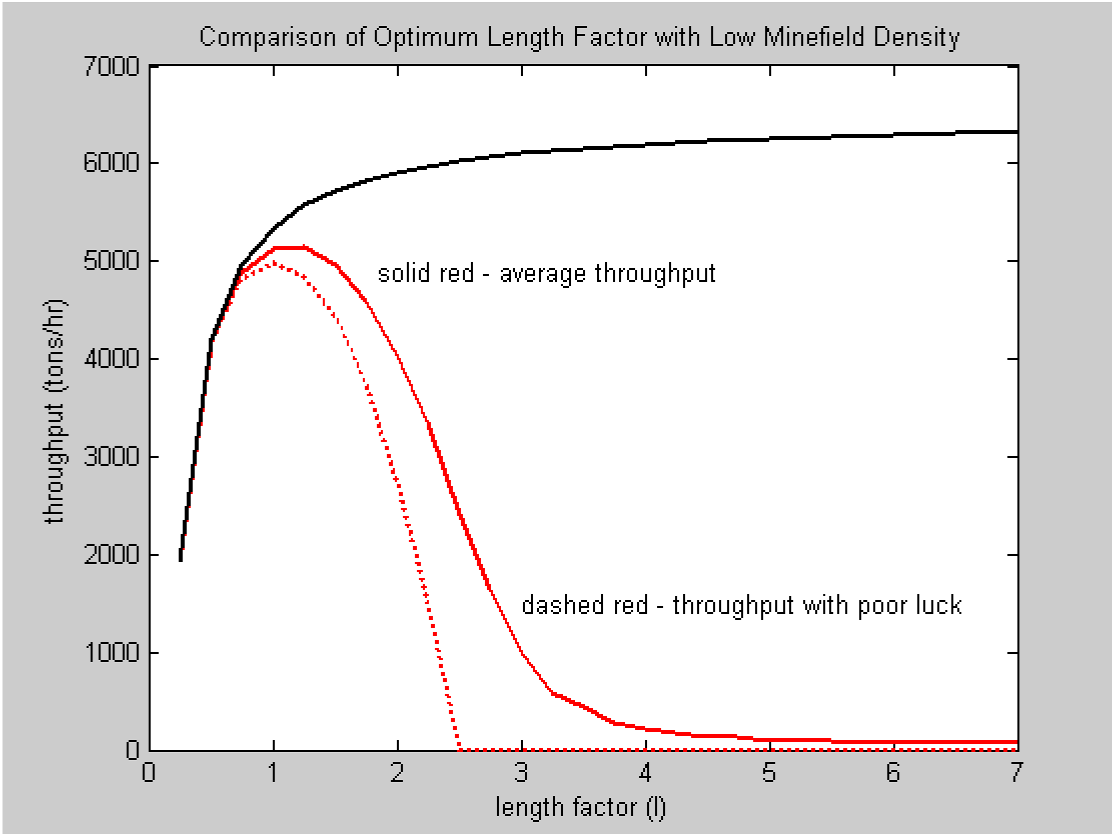

Figure 17. Throughput of high density minefield with poor luck

The changes in the low density minefield were the smallest. This is due to the risk already being relatively high for each ship, and the higher risk from poor luck.

In all cases, the optimum length factor decreased when considering poor luck. This information gives the planner the ability to see the impacts of bad luck on the throughput. Given this information, a throughput with the size and quantity of ships in a length factor of four or above is unthinkable, even with a very low minefield density.

3. Problems in Throughput Modeling

Several problems came up in modeling the throughput as described previously. One of the largest problems came about when modeling the desired total displacement and number of ships. As described before, the total displacement is held constant, or Δ = constant * (l^3* n). To accurately compare differing systems of ships in this equation, the

number of ships can sometimes be a non-integer. The values for how many ships are required for each length factor are shown in Table 8.

Number of Ships	Length Factor
21952.00	0.25
2744.00	0.50
813.04	0.75
343.00	1.00
175.62	1.25
101.63	1.50
64.00	1.75
42.88	2.00
30.11	2.25
21.95	2.50
16.49	2.75
12.70	3.00
9.99	3.25
8.00	3.50
6.50	3.75
5.36	4.00
4.47	4.25
3.76	4.50
3.20	4.75
2.74	5.00
2.37	5.25
2.06	5.50
1.80	5.75
1.59	6.00
1.40	6.25
1.25	6.50
1.12	6.75
1.00	7.00

Table 8. Number of ships for each length factor

This made analysis of such a system difficult since risk is assessed for an entire ship, not merely a fraction of a ship. To properly obtain results, the first method was to round the number of ships to the nearest integer. This gave poor results as is demonstrated in Figure 18.

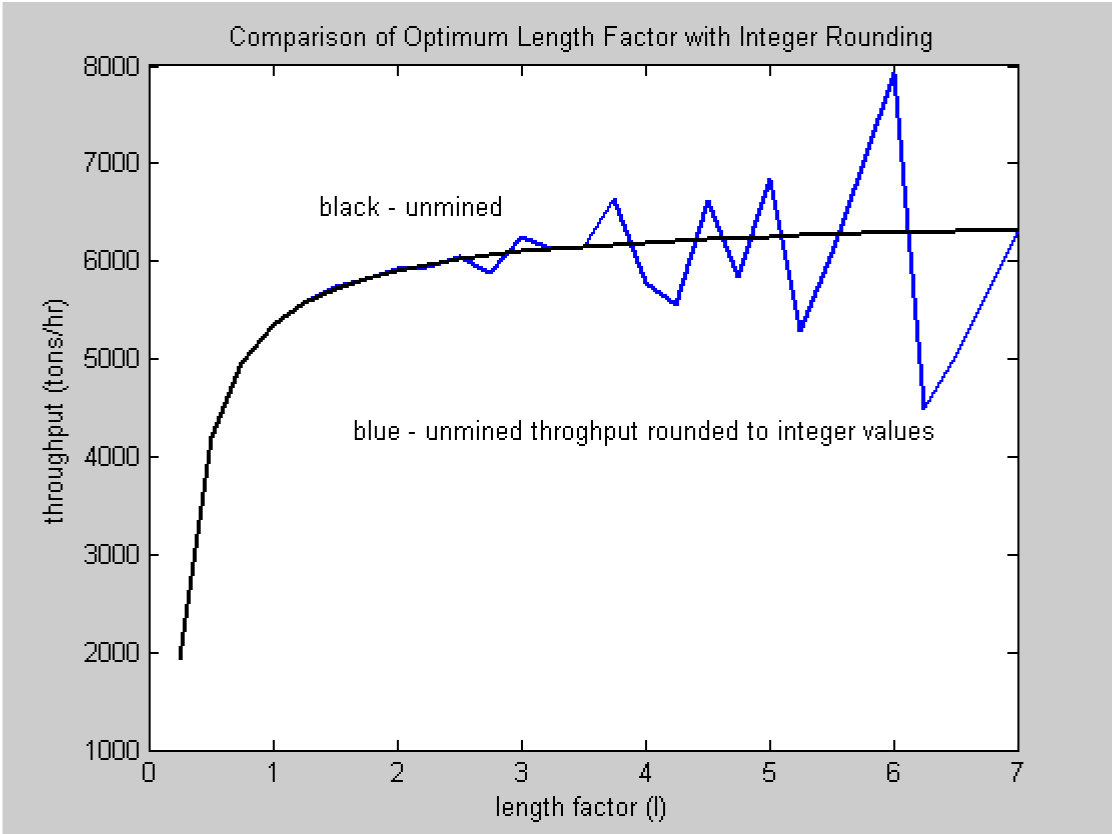

Figure 18. Demonstration of rounding to nearest integer values

Next, rounding down and up were considered with their results in Figure 19. Notice how the integer rounding seeks both above and below the decimal-computed curve. These results were initially used with a high density minefield and found to be acceptable in such a case since the survivability of the higher length factors in the high density minefield reduced the impact of the noise. Once lower density minefields were introduced, the rounding error noise was no longer acceptable since the rounding errors were more significant than the impact of the mines. This led to errors in computing the maximum length factor. Other rounding methods were sought to correct this issue. These other methods of rounding are shown with their results below in Figure 19.

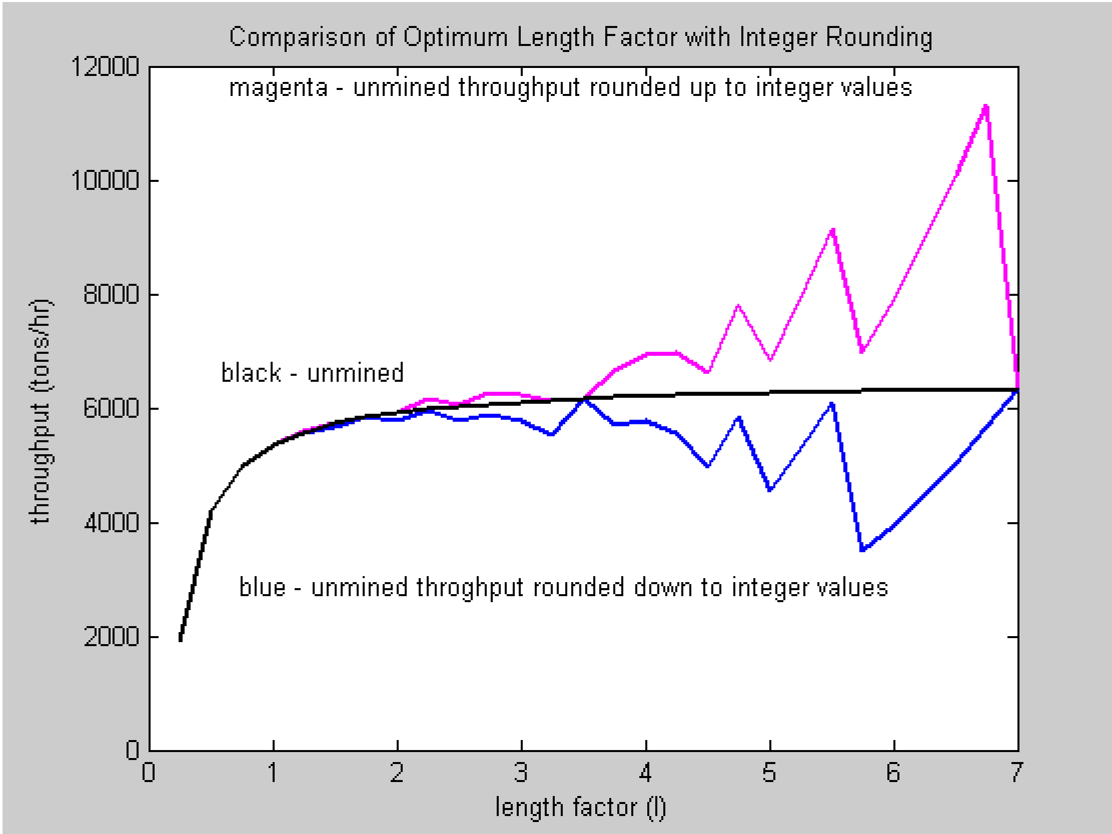

Figure 19. Demonstration of rounding up and down to nearest integer values

As is shown in the figure above, the rounding error noise was not corrected when using other rounding techniques. This noise stems from rounding errors that become more prevalent as the number of ships decreases. Rounding up a 20 ton displacement ship up one has a much smaller impact than rounding a 6000 ton ship up one. This is the case in the above graph. When the length factor is 1, the displacement is about 20 tons per ship. When the length factor is 6.75, the displacement is about 6000 tons.

Note, though, that the length factor at seven always yields the correct throughput. This is since the length factor at seven is never rounded. It is always exactly one ship at this length factor.

Producing acceptable results even in low density minefields required pro-rating the remainder of the last ship to a portion of the displacement. While this method does technically produce a ship of smaller size for the last remainder value, it does smooth out the throughput approximations and allow for analysis with minefield risk. Considering

all available methods, this method appears to produce good results despite having some conceptual comparison problems with producing a smaller ship with the round-off values. Results are shown below between actual constant throughput and proportional remainder throughput values in Figure 20.

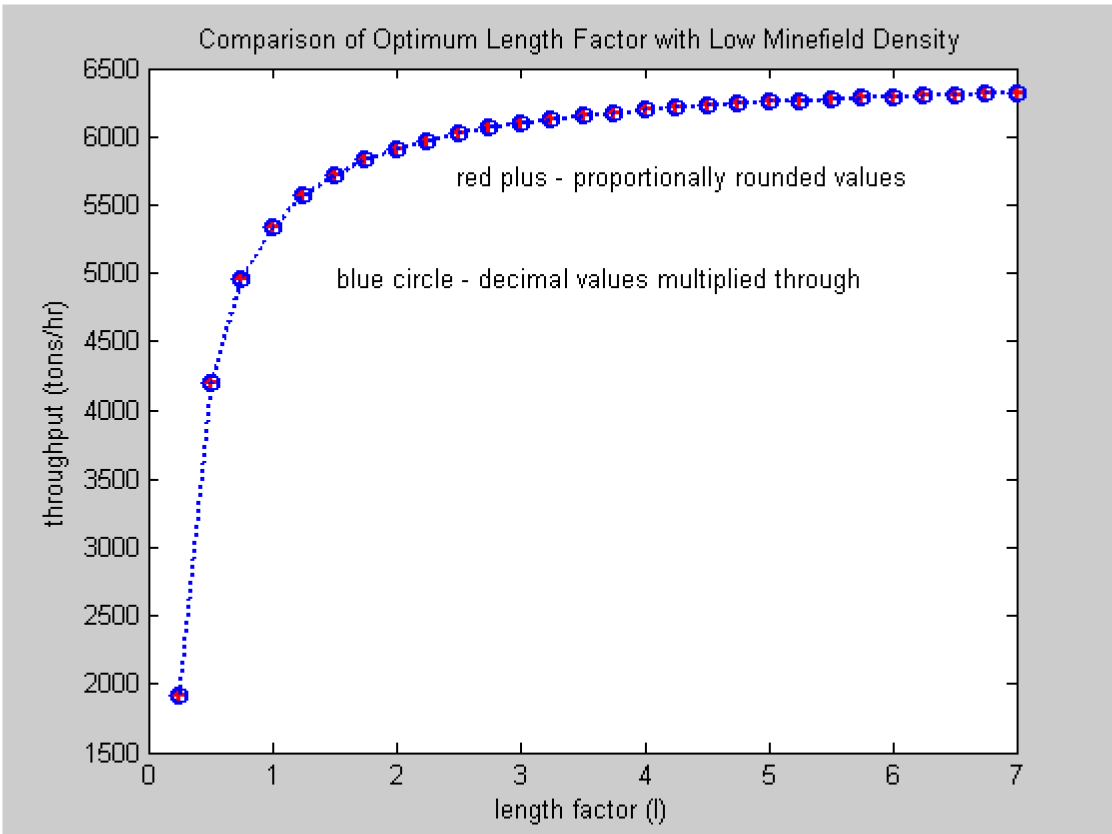

Figure 20. Demonstration of proportional rounding with decimal multiplication values

Note how these two curves effectively overlap. Use of this method was used to obtain smoother curves when analyzing minefields of varying densities. Upon comparing the numerical results of these graphs, they were found to be effectively the same values, differing only by values in the range of 1^{-10}. Still, this method offers some problems since the last ship though proportional in weight must still accept the full risk associated with a full-sized craft of that size. The impact of this simplification is minor and still produces good comparative results, but it is nonetheless a fact to consider.

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IV. RESULTS AND CONCLUSIONS

A. RESULTS OF THROUGHPUT OPTIMIZATION

1. Sizing Comparison with Current Military Ships

Though the purpose of the optimization was to observe and analyze optimum sizing of an idealized container vessel, it also is useful to compare the length factor with current military vessels. Since displacement is proportional to the length factor cubed, it was a simple exercise of multiplying the base displacement at a length factor of one by the length factor cubed. This gives the blue curve in Figure 21. Then, observing the displacement of current military ships in Jane's allows for the observer to see the approximate length factor for that size of ship [11], [12].

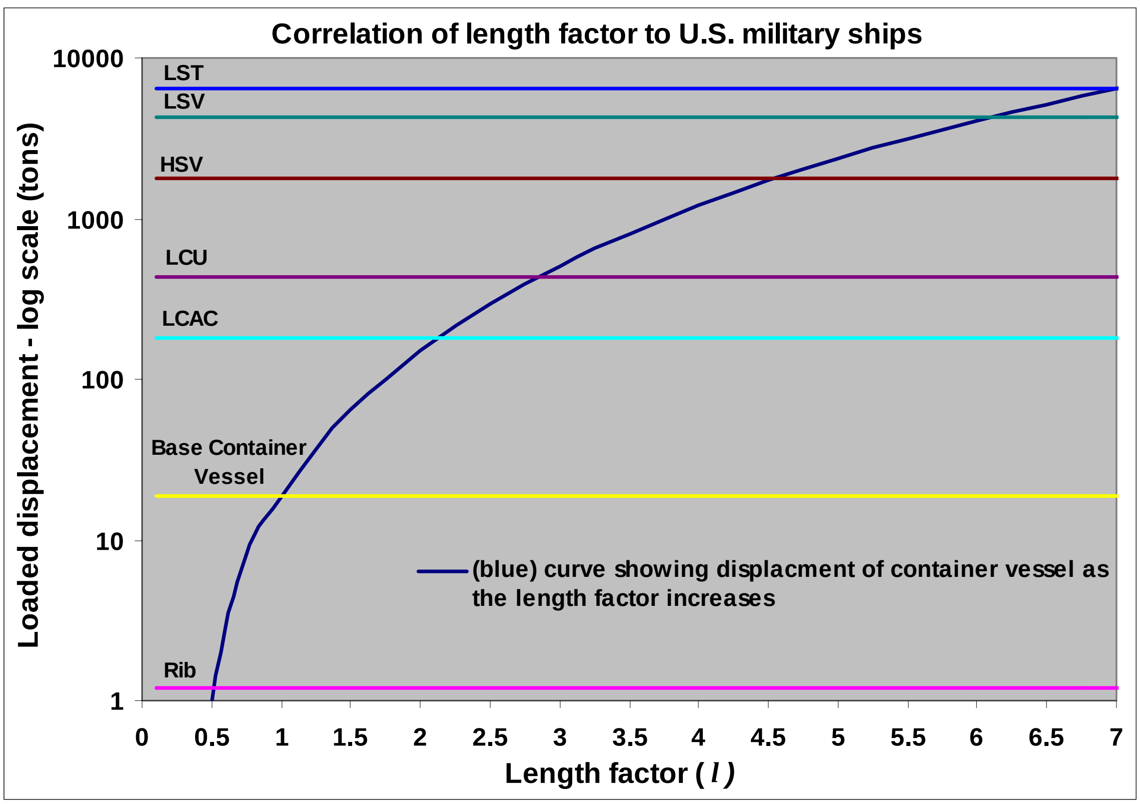

Figure 21. Correlation of length factor to U.S. military ships

The ships shown in the figure above are all amphibious supply-type U.S. ships. These ships are the primary littoral supply vessels currently used by the U.S. armed forces. Their basic shape does not scale directly with the length factor, and they are shown for illustrative purposes only. The ships are comprised of a rib, LCAC, LCU, HSV, LSV, and LST. These ships are shown in the figures below.

Figure 22. Rib watercraft (from [11])

Figure 23. LCAC naval vessel (from [11])

Figure 24. LCU supply ship (from [11])

Figure 25. HSV experimental craft (from [11])

Figure 26. LSV currently used by the U.S. Army (from [11])

Figure 27. LST (currently in the inactive reserve) (from [12])

Figure 21 gives a rough idea for the scale in sizing according to the length factor optimization. The optimum length factor for all situations requires that each variable be considered. In addition, minefield density and the poor luck factor curves should also be considered.

2. Sizing Results from Throughput Optimization and Survivability Considerations

Optimization of the length factor yielded results that varied drastically. The data points varied from an optimum length factor of 0.5 all the way up to a max of 4.75. Averaging the high, medium and low density minefields yields what is shown in Table 9.

Minefield Density Optimum (Averages)		
Low	**Intermediate**	**High**
2.91	1.83	1.25

Table 9. Average minefield density optimum length factor (*l*) values

This shows that the optimum values when considering all factors is between 1 and 3. The optimum length factor of the ship should be selected toward the smaller end of this due to the drop in optimum points when considering poor luck. A safe range of optimum length factors in all densities should be in the range of 1-2. Since the fidelity in the data is only within a length factor of 0.25 and the exact operating conditions are not defined, selecting a more precise value is not possible at this time.

B. CONCLUSIONS

1. Optimum Length Factor Conclusions and Further Areas of Study

Through the analysis, a range for the optimum length factor was discovered. The tools used did give some insight to the sizing and quantity of compatible ship systems. In comparing the systems as defined, it was somewhat surprising to discover that the idealized box container vessel performed within the range of optimum values.

If such a container vessel progresses to further stages of development, then the optimum length factor can be narrowed when a better operating envelope is declared.

Currently, the operating values for range, speed, SFC, and loading factor are simply too diverse to obtain a single value for length factor. Additionally, cost is an essential part of a complete optimization picture. Cost of the comparative systems as length factor increases is therefore recommended for further analysis. Once more definition is given for the operating range and speed for this vessel, more progress can be made in further narrowing the optimum length factor for supply.

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APPENDIX. MATLAB CODE

```
%-----------------------------------------------------------------------
% Notes and special thanks for this Uncountered Mine Planning Model
%-----------------------------------------------------------------------
% This Matlab code is written by LT William Sumsion for thesis work.
% All rights reserved, (c) 2008.
% Special thanks to Dr. Alan Washburn and Dr. Carlos Borges (both of
% Naval Postgraduate School) for their help.
% Adapted from Excel file and Visual Basic code used by Dr. Washburn
% for UMPM modeling, but altered to allow for additional transitors
% through a minefield, including modifications for matrix alegebra
% instead of spreadsheet cell recalls
%-----------------------------------------------------------------------
% Notes on inputs for this function
%-----------------------------------------------------------------------

% x = number of ships
% d = damage radius
% w = minefield width
% a = mine actuation prob, but will be adjusted to A(x) (see Washburn)
% m = number of mines
% sh = shape of curve, altered by user to fit desired mine profile
% sc = scale of curve, altered by user to fit desired mine profile

clc
clear

x = 25;
d = 50;
w = 5000;
m = 250;
a = (1/2);
scale = 30;
shape = 3;

%-----------------------------------------------------------------------
% Actuation Probability
%-----------------------------------------------------------------------

% I = incrament vector
I = linspace(0,1,101)';

A = (a*(1-exp(-(scale./(I.*d)).^shape)'))';

%-----------------------------------------------------------------------
% Numerical grid for calculating numerical integrals
%-----------------------------------------------------------------------

G = zeros(101,x+1);
q = 1;
for q = (1:101);
```

```
    n=2;
        for n = (2:x+1)
            G(q,n) = 1-(1-A(q))^(n-1);
            n=n+1;
        end
    q=q+1;
end

%-----------------------------------------------------------------------
% Numerical integral calculation
%-----------------------------------------------------------------------
IC = zeros(x+1,1);
n=2;
    for n=2:(x+1)
        IC(n,1) = 0.02*d*(sum(G(:,n)) - ((1/2)*(G(1,n)+G(101,n))));
    end
Rx = IC./w;

%-----------------------------------------------------------------------
% Casualty distribution and threat profile calculation using UMPM
%-----------------------------------------------------------------------

if 2*d > w
    d = w/2;
    warning('the damage radius has been reset to 1/2 the minefield
width.')
end

% The 'P' matrix below is used to solve for the casualty distribution
P = zeros(m+1, x+1);
k=1;
for k = 1:x
        i=1;
        for i = 1:k
        P(1,i) = 0;
        i = i+1;
        end

        P(1, k+1) = 1;
        j=2;
        for j = 2:(m+1)
                for i = 1:k
                P(j, i) = (P(j-1,i) * (1-Rx(i)))+(P(j-1, i+1)*Rx(i+1));
                i = i+1;
                end
        P(j, k+1) = P(j-1, k+1) * (1 - Rx(k+1));
        j = j+1;
        end

% The 'E' matrix below is used to solve for the threat profile

        E(1)=0;
        E(k+1) = 0;
        i=1;
```

```
        for i = 1:k
        E(k+1) = E(k+1) + (i * P(m+1,((k-i)+1)));
        i = i+1;
        end
k = k+1;
end

%-----------------------------------------------------------------------
% Casualty Distribution output vector
%-----------------------------------------------------------------------

i=1;
for i=1:x+1
    AR(i)=P(m+1,((x+2)-i));
end
AR=AR';
Casualty_Distribution = AR

%-----------------------------------------------------------------------
% Integration of Casualty Distribution
%-----------------------------------------------------------------------

i=1;
S=zeros(x,1);
for i=2:x+1
    S(i) = S(i-1) + (AR(i-1));
    i=i+1;
end

C =1-S;
s=0;
i=1;
while s<0.90
    s = s + AR(i);
    i=i+1;
end
Ninety_Five_percent_probability_casualties = i-1
Ship_number_for_ninety_percent = s;

%-----------------------------------------------------------------------
% Threat Profile output vector
%-----------------------------------------------------------------------

for i = 1:x
    ER(i) = E(i+1) - E(i);
i=i+1;
end
ER=ER';
Threat_Profile = ER

%-----------------------------------------------------------------------
% Mean Casualty Calculation
%-----------------------------------------------------------------------
```

```
Mean_Casualties = sum(ER)

%------------------------------------------------------------------------
% Plots to demonstrate data performance of transiting through minefield
%------------------------------------------------------------------------

N = linspace(0,x,x+1)';
NN = linspace(1,x,x)';

figure(1)
plot(N,AR,'r+-')
title('Casualty Distribution')
xlabel('Number of Casualties')
ylabel('Probability')

figure(2)
plot(NN,ER,'bo-')
title('Threat Profile')
xlabel('Transitor Number')
ylabel('Probability')
axis([0 x 0 1])

figure(3)
plot(I,A,'m --')
title('Half Actuation Curve out to Damage Radius')
xlabel('Fraction of Damage Radius')
ylabel('Probability of Mine Explosion')
axis([0 1 0 1])

figure(4)
plot(N,C) %Put in "C" for Casualties and "S" in for survivors
title('Integration of Casualty Distribution')
xlabel('Number of Casualties')
ylabel('Total Probability')
axis([0 x 0 max(C)])

%------------------------------------------------------------------------
% Throughput Analysis from Mingtze Yeh's Thesis, NPS, 2007
%------------------------------------------------------------------------

i_frame=0;
PropC = 0.4;

% Set min and max values
% loading fraction (%)
LF_min = 10;
LF_max = 80;
LF_inc = 10;
% specific fuel consumption (lbs/hr/HP)
SFC_min = 2.80;
SFC_max = 0.60;
SFC_inc = 0.20;
% range (NM)
```

```
range_min = 10;
range_max = 100;
range_inc = 10;
% speed (kn)
speed_min = 30;
speed_max = 60;
speed_inc = 10;


% Loading fraction
i=0;
for iLF = LF_min:LF_inc:LF_max,
    LF = iLF;
    LF_string = num2str(LF);
    % Specific fuel consumption
    for iSFC = SFC_min:SFC_inc:SFC_max,
        i_frame = i_frame+1;
        SFC = iSFC;
        SFC_vector = SFC;
        SFC_string1 = num2str(100*SFC);
        SFC_string2 = num2str(SFC);
        for ilength_ratio =
length_ratio_min:length_ratio_inc:length_ratio_max
            i = i+1;
            length_ratio=ilength_ratio;
            length_vector(i)=length_ratio;
            length_ratio_string=num2str(length_ratio);
            length=length_ratio*20;
            beam=length_ratio*8;
            % Begin calculations
            T = [(52895*LF*35)/(100*2240*beam*length)];     % draft,
            %52895 is 100% LF for 20x8x8 box container, 35 is ft^3/ton
            W = [52895*LF*ilength_ratio^3/(100*2240)];      % weight
            %2240 is lb/ton
            lamda(i) = [52895*LF*ilength_ratio^3/(100*2240)];

            I = 0;
            for II = range_min:range_inc:range_max,
                I = I+1;
                Range = II;
                range_vector(I) = Range;
                J = 0;
                for JJ = speed_min:speed_inc:speed_max,
                    speed_string=num2str(JJ);
                    J = J+1;
                    Speed = JJ;
                    Froude=Speed*1.68781/sqrt(32.2*length);
                    %1.68781 converts knots to ft/s
                    EHP_ini = 1088.1*Froude^2 - 309.21*Froude + 23.533;
                    EHP_nom = EHP_ini * (160 + 56 * T) /(160+56* 4.16);
                    EHP_int = EHP_nom * (length/20)^2;
                    EHP = .01944*Speed^3*W^(2/3);%scaled EHP
                    TotalPower = [EHP/PropC];
                    Time2Dest = [Range/Speed];
                    Fuel = [(SFC*TotalPower*Time2Dest)/2240];
```

```
                    Payloadpertrip = [W-Fuel];
                    Tonsperhr = [Payloadpertrip/Time2Dest];
                    if  Tonsperhr < 0
                    Tonsperhr = 0;
                    end
                    tph_vector(i,J) = Tonsperhr;
                    speed_vector(J) = Speed;
                end
            end
        end
            for nn = 1:1:((length_ratio_max-
length_ratio_min)/length_ratio_inc)+1;
                n_vector(nn)=lamda(i)/lamda(nn);
            end
        for III=1:1:((length_ratio_max-
length_ratio_min)/length_ratio_inc)+1;

tph_w_surv(III) = sum((1-ER(1:ceil(n_vector(III)))).*tph_vector(III));
%this is rounded up
tph_w_surv_t(III)=sum((1-ER(1:round(n_vector(III)))).*tph_vector(III));
%this is averaged
tph_w_surv_n(III)=sum((1-ER_n(1:ceil(n_vector(III)))).*tph_vector(III))
%no survivability rounded up
tph_w_s_nt(III)=sum((1-ER_n(1:round(n_vector(III)))).*tph_vector(III));
%no survivability averaged
tph_w_s_ntt(III)= sum((1-ER(1:fix(n_vector(III)))).*tph_vector(III));
%rounded down
tph_w_s_tt(III)=sum((1-ER_n(1:fix(n_vector(III)))).*tph_vector(III));
%no survivability rounded down
tph_w_s_ntt_q(III)= sum((1-ER(1:fix(n_vector(III)))).*tph_vector(III));
%rounded down with non-integer fix
tph_w_s_tt_q(III)=sum((1-ER_n(1:fix(n_vector(III)))).*tph_vector(III));
%no survivability rounded down
            if  n_vector(III)-fix(n_vector(III))>0

tph_w_surv_tt_q(III)=tph_w_surv_tt_q(III)+((n_vector(III)-
fix(n_vector(III)))/(ceil(n_vector(III))))*sum((1-
ER_n(1:ceil(n_vector(III)))).*tph_vector(III)); %see if corrects noise

tph_w_surv_ntt_q(III)=tph_w_surv_ntt_q(III)+((n_vector(III)-
fix(n_vector(III)))/(ceil(n_vector(III))))*sum((1-
ER(1:ceil(n_vector(III)))).*tph_vector(III));%see if corrects noise
            end
        end
    end

            [greatest, index] =  max(tph_w_surv_ntt_q);
            maximum_length_factor(UUU) =
(index*length_ratio_inc)+(length_ratio_min-length_ratio_inc);
            MLF=maximum_length_factor;

TT=linspace(length_ratio_min,length_ratio_max,(((length_ratio_max-
length_ratio_min)/length_ratio_inc)+1));
            IIII=IIII+1;
```

```
end
            ex_plot(UUU,:)=tph_w_surv_ntt_q;

end
            figure(5)

            plot(TT, ex_plot(1,:),'m', 'LineWidth', 2)
            hold on
            title('Comparison of Optimum Length Factor with Varying
            Minefield Density')
            xlabel('length factor (l)')
            ylabel('throughput (tons/hr)')
            plot(TT, ex_plot(2,:),'b', 'LineWidth', 2)
            plot(TT, ex_plot(3,:),'r', 'LineWidth', 2)
            plot(TT, tph_w_surv_tt_q,'k', 'LineWidth', 2)
            plot(TT, (lamda.*n_vector)/(Time2Dest),'y', 'LineWidth', 2)
            plot(TT, (tph_vector.*n_vector'),'k', 'LineWidth', 2)
            gtext('black - unmined')
            gtext('magenta - low density minefield')
            gtext('blue - intermediate density minefield')
            gtext('red - high density minefield')
            %axis([0 7 0 ceil(max(lamda.*n_vector)/(Time2Dest))])
            hold off
```

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